PRESSURIZED WATER REACTOR SUMP PERFORMANCE EVALUATION METHODOLOGY

May 28, 2004

ACKNOWLEDGMENTS

This guidance document, PWR Containment Sump Evaluation Methodology, was developed by Westinghouse and Alion Science and Technology under the sponsorship of the Westinghouse and B&W Owners Groups and under the technical guidance of the NEI PWR Sump Performance Task Force.

NOTICE

EXECUTIVE SUMMARY

In response to Generic Safety Issue 191 (GSI-191), "Potential of PWR Sump Blockage Post-LOCA," Nuclear Energy Institute and the industry formed the PWR Sump Performance Task Force. The primary purpose of the Task Force was to interface with the U.S. Nuclear Regulatory Commission as the issue developed and to champion creation of a methodology document that could be used as a guideline for PWR operators to address the issue. Much of the previous testing and evaluations supporting the Utility Resolution Guide (URG) for BWRs was used as appropriate. However, it was determined early that a standard "cookbook" could not be created for PWRs for several reasons. PWRs vary greatly in containment size, floor layout, sump configuration, required ECCS flows, insulation types and location, and post-LOCA operational requirements. Since it was evident that one guideline could not encompass all PWRs, the NEI methodology document provides basic guidance on approach and various methods available, but recognizes that the best strategy for each plant could involve a combination of methods. Each PWR operator, having unique knowledge of specific plant design and operation, is best qualified to determine the optimum solution strategy. As such, this document does not prescribe a specific combination of methods to the user.

This methodology document provides guidance to each utility in all primary issues that are required to be addressed in resolving this issue. It is to be considered a draft document for purposes of this review. The document picks up after NEI 02-01, which provides guidance on the performance of plant condition assessments and appropriate supporting walkdowns for collecting information to support the methods discussed in this document. This document addresses the major technical components, including debris generation/distribution, debris transport, screen head loss, and pump NPSH. The current document has several open areas that require either more study or testing to address. They include the treatment of long-term chemical effects and calcium silicate head loss correlations. A downstream effects evaluation, a key component of issue closure, is under development. This document also does not address the implementation and/or licensing of any design or operational changes resulting from the use of the evaluation methodology.

Section 1 contains an introduction to the PWR strainer debris issue, including a historical review describing the steps that led to the current understanding. Section 2 is a high-level summary of the overall process considerations that need to be addressed during the evaluation process, while Section 3 describes a Baseline Evaluation Method that may be applied to all PWR's and provides sample calculation using the Baseline Evaluation Method. In Section 5, refinements in administrative control and design are discussed. Section 6 provides a guidance on a risk-informed evaluation. Section 7 provides guidance for additional design considerations.

This Page Intentionally Left Blank

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES (Cont'd)

1 INTRODUCTION

1.1 ISSUE DESCRIPTION

The postulated rupture of a pipe located inside containment and carrying high-energy fluid is one of the key factors used in development of the licensing, design, and operational requirements for nuclear reactors. Although the probability of a high-energy line break (HELB) in a large pipe is extremely low, it is an event that reactors are designed to withstand, without jeopardizing the health and safety of the public. This design basis accident (DBA) is referred to as a loss-of-coolant-accident (LOCA). For some pressurized water reactors (PWRs), a main steam line break may need to be included if the emergency core cooling system (ECCS) is required.

Should such an event ever occur, the high-energy fluid has the potential to damage adjacent equipment and material. This LOCA-generated debris, including particulates, fibers, and reflective metal insulation (RMI) foils, may be transported and result in debris blockage of the ECCS and containment spray system (CSS) pump suction strainers. This scenario raises concerns that the head loss across the suction screens may exceed the available net positive suction head (NPSH) margin. As a result, the Nuclear Regulatory Commission (NRC) has determined that the potential for PWR core damage presents a risk significant enough to warrant evaluation at every plant, to ensure sufficient NPSH margin exists in the event of this type of accident.

It should be noted that the determination of pipe break locations, zones of influence (ZOI), and other calculational bases described herein are solely for ECCS strainer design purposes and are not intended to replace the plant licensing or design bases for other purposes.

1.2 HISTORICAL OVERVIEW

The NRC initially addressed post-accident sump performance under Unresolved Safety Issue USI A-43. Research on BWR ECCS suction strainer blockage identified new phenomena and failure modes that were not considered in the resolution of A-43. In addition, operating experience identified new contributors to debris and possible blockage of PWR sumps, such as degraded or failed containment paint (coatings). Thus, the NRC Generic Safety Issue GSI-191, “Assessment of Debris Accumulation on PWR Sumps Performance,” was identified in 1998 by Footnotes 1691 and 1692 of NUREG-0933. The NRC also initiated an expanded research effort to address these new safety concerns for PWRs.

On September 28, 2001, the NRC issued report LA-UR-01-4083, “GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance,” (Reference 58). In issuing this report, NRC Research had determined that post-accident sump blockage is a generic concern for PWRs. Based on this determination, the PWR industry undertook an effort to develop guidelines that are universally applicable to all PWRs and may be used by all licensees to evaluate the post-accident performance of a plant’s containment sump. These guidelines and associated methodology are presented in this document.

1.3 ASSUMPTIONS

This section contains the assumptions for the development of an evaluation methodology to address the potential for containment sump screen blockage following a design basis event. This evaluation methodology (EM) will be used in support of plant-specific evaluations that address concerns identified in GSI-191.

The major assumptions are:

1. Application of Single Failure

   Consideration of the initiating event will be based on current design analysis principles. Component and system failure will be limited to credible single failure scenarios. Only one limiting failure will be applied to the entire analysis, and the effects of that failure will be consistently applied to all phases of the plant response. Expected non-faulted system initial conditions, timing, and operating characteristics will be assumed.

2. Evaluation Methodology Scope to Address Materials Typically Used in Industry Applications

   The evaluation methodology will address materials typically used in the industry as insulation and coating materials. The guidance will not necessarily explicitly consider or assess the generation, transport, or accumulation characteristics of non-traditional materials (i.e., materials used in a single plant or rare applications).

3. Application of Risk-Informed Considerations

   Program methodology is developed primarily using deterministic methods. Risk-informed considerations, where practical and defensible, may also be used. It is anticipated that such considerations may be employed in establishing initial conditions, timing and operating characteristics of plant systems and components.

4. Validity of Supporting Data

   Data employed in the development of the evaluation methodology or applied directly through the evaluation methodology may not have been produced under a 10 CFR 50, Appendix B program. Such data will be carefully evaluated through a validation and verification process that may include analytical methods such as comparison to theoretical predictions or to other similar but independent empirical results.

The following definitions are used throughout this document to describe some of the more common terms used to describe the various activities related to this issue.

Break-Generated Debris – The remains of broken or dislodged materials (for example, insulation, coatings, tape, and dust) generated by the action of high-energy fluid released from a postulated break in a high-energy line inside containment.

Emergency Core Cooling (ECC) Sumps – Active sumps in the reactor containment building used to recirculate coolant for long term decay heat removal from the reactor core and/or the containment environment.

Encapsulated Insulation – Encapsulated insulation is insulation covered on all surfaces by sheet metals or fiberglass cloth. Examples of encapsulated insulation include RMI and calcium silicate cassettes.

Jacketed Insulation – Jacketed insulation is insulation that is covered on the outside surface of the pipe by a wide variety of materials. Examples of jacketed material include metal sheets, solid fiberglass and calcium silicate wrapped with aluminum foil.

Latent Debris – Latent debris is defined as unintended dirt, dust, paint chips, fibers, pieces of paper (shredded or intact), plastic, tape, or adhesive labels, and fines or shards of thermal insulation, fireproof barrier, or other materials that are already present in the containment prior to a postulated break in a high-energy line inside containment. Dust and dirt include miscellaneous particulates that are already present in the containment prior to a postulated break. Potential origins for this material include activities performed during outages and foreign particulates brought into containment during outages.

Wrapped Insulation – Insulation that is covered on the outside by non-metallic wrapping. Typically, the wrapping is an epoxy impregnated fiberglass mesh that is either fastened to the insulation by tie wraps or glued to the insulation.

Zone of Influence (ZOI) – The zone of influence represents the zone where a given high-energy line break (HELB) will generate debris that may be transported to the sump. The size of the ZOI will be defined in terms of pipe diameters and will be determined based on the pressure contained by the piping and the destruction pressure of the insulation surrounding the break site. Three recommended methods for determining the ZOI are:

- The size of the spherical ZOI can be calculated based on the insulation with the lowest destruction pressure, and all insulation contained within the ZOI is assumed to be damaged such that it becomes debris, regardless of insulation type.

- For each insulation type, a separate spherical ZOI may be calculated.

- The ZOI is defined by a freely expanding jet.

The destruction pressure for each type of insulation is addressed as follows. The pipe break radial offset may be accommodated in the calculation of the spherical ZOI size. Similarly, pipe restraints may be accommodated in the calculation of the spherical ZOI size.

1.4 ACRONYMS

AJIT	Air Jet Impact Test
ARL	Alden Research Laboratory
ASJ	all-service jacketing
BWROG	Boiling Water Reactor Owners’ Group
CAD	computer-assisted design
CEESI	Colorado Experimental Engineering Station, Inc.
CFD	computational fluid dynamics
COA	Candidate Operator Action
CSHL	clean strainer head loss
CS	containment spray
CSS	containment spray system
DBA	design basis accident
DBHL	debris bed head loss
DEGB	double-ended guillotine break
ECC	emergency core cooling
ECCS	emergency core cooling system
EM	evaluation methodology
EOP	Emergency Operating Procedure
ERG	Emergency Response Guideline
FME	foreign materials exclusion
GSI	Generic Safety Issue
HELB	high-energy line break
HPSI	high-pressure safety injection
IOZ	inorganic zinc
LANL	Los Alamos National Laboratory
LDFG	low-density fiberglass
LDSE	Low Density Silicone Elastomer
LOCA	loss-of-coolant accident
NEI	Nuclear Energy Institute
NPSH	net positive suction head
NRC	Nuclear Regulatory Commission
OEM	original equipment manufacturer
OPG	Ontario Power Generation
PSE	Plant Support Engineering
PWR	pressurized water reactor
QA	quality assurance
RAI	Request for Additional Information
RCDT	reactor coolant drain tank
RMI	reflective metal insulation
RWST	refueling water storage tank
SEM	scanning electron microscope
SER	Safety Evaluation Report
SI	safety injection
SS	Stainless steel

TBE	thin-bed effect
TKE	turbulent kinetic energy
TSHL	total strainer head loss
UNM	University of New Mexico
URG	Utility Resolution Guide
ZOI	zone of influence

1.

2 EVALUATION METHODOLOGY OVERVIEW

The methodology described in this document provides guidance for use in evaluating the susceptibility of PWR containment sumps to blockage resulting from the effects of a postulated LOCA. This methodology is based on published studies encompassing the body of knowledge related to debris generation, debris transport and debris head loss following high energy line breaks in nuclear power plants.

The processes and phenomena associated with debris generation, debris transport and headloss are complex. The existing body of knowledge, while extensive, has known limitations that introduce uncertainties in the translation and application of the knowledge base to plant-scale conditions and the wide variability of designs present in PWR containments introduce a need to conservatively apply available data. There is the added difficulty and expense of modeling the large-scale non-linear flow processes affecting debris transport in PWR containments, leading to a need, where possible, to simplify the computational effort.

The evaluation methodology addresses these analytical complications using a process that helps guide the user in developing a technically sound resolution that meets the needs of individual PWR plants. An overview of the evaluation process is shown in Figure 2-1. In general, the containment sump size appropriate for a plant is proportional to the level of conservatism used in the supporting analysis. Resources can either be directed toward refining the analysis methodology (i.e., removing excess conservatism) in order to support a smaller screen size or toward implementation of design modifications (e.g., a larger screen size, replacement of insulation). The appropriate direction will depend on factors that will vary from plant to plant. The evaluation methodology attempts to support this decision process in a step-wise fashion that begin with a conservative baseline set of methods (Section 3) that help identify the dominant design factors for a given plant, followed by separate guidance on possible refinements to the baseline analytical methods (Section 4) and potential design/operational refinements (Section 5).

It is important to note that the Baseline evaluation can be performed utilizing either the current plant configuration or by directly incorporating planned design/operational changes. Performance of the Baseline with planned changes allows a means to assess known areas of susceptibility to screen blockage and enables planned changes to be directly incorporated into the final resolution process.

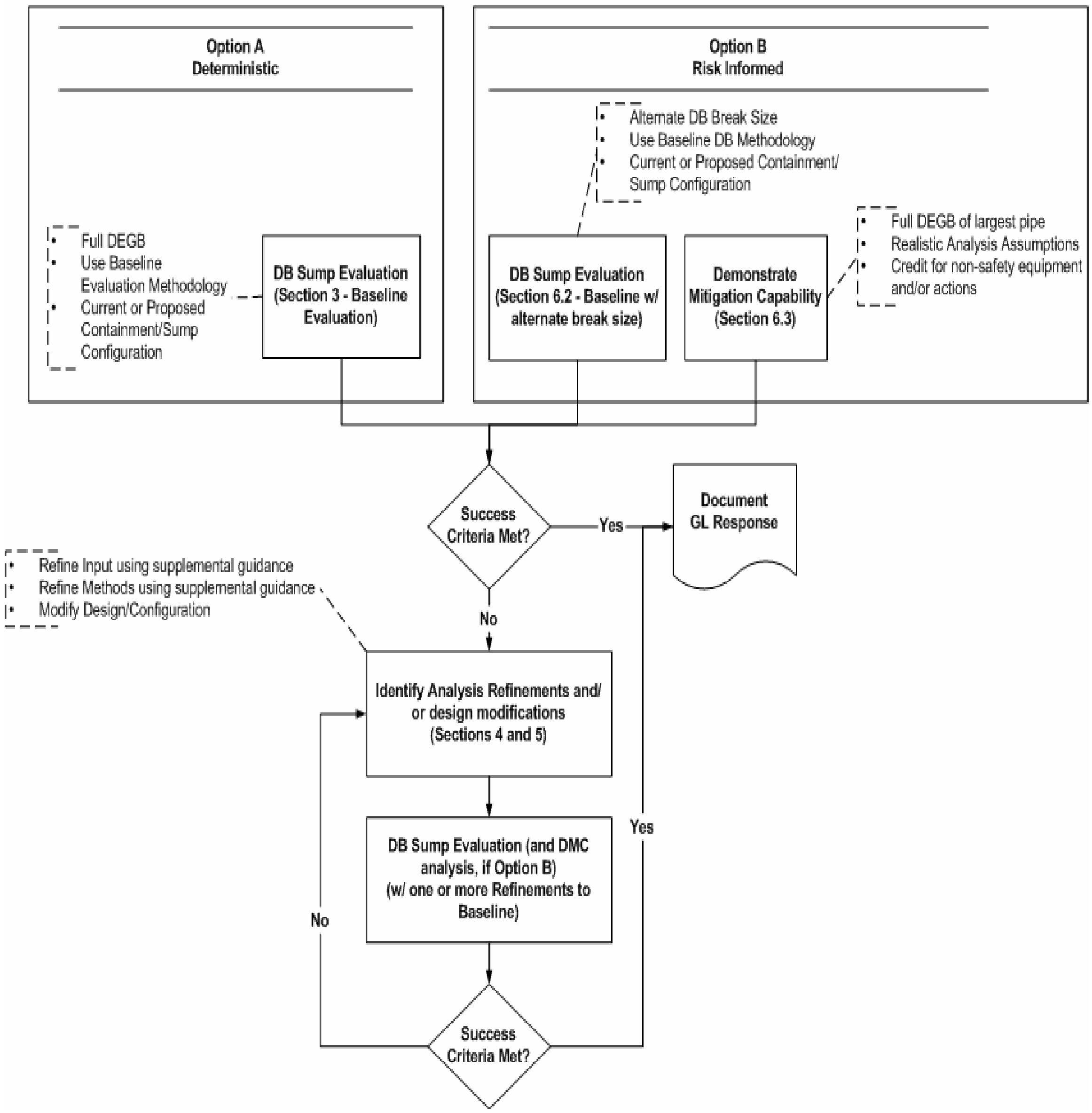
The evaluation methodology allows for incorporation of either a deterministic evaluation process (Option A) or a risk-informed evaluation process (Option B). The risk-informed evaluation process utilizes industry and NRC efforts to risk-inform Title 10, *Code of Federal Regulations* Section 50.46, "Acceptance criteria for emergency core cooling system for light-water nuclear power reactors," as a suitable technical basis for defining a spectrum of break sizes for debris generation and containment sump strainer performance.

The risk-informed evaluation process (Section 6) allows for use of an alternate maximum break size in analyses that provide additional assurance of fulfilling the long-term cooling requirement of 10 CFR 50.46 and involves two separate analysis steps: 1) a design basis analysis using an alternate maximum break size, and 2) an analysis that demonstrates beyond-design-basis mitigation capability.

In implementing the Option B approach and use of an alternate break size, it is necessary to demonstrate that an adequate degree of mitigation capability is retained for break sizes between the new maximum break size and the double-ended guillotine break of the largest pipe in the reactor coolant system. This "beyond-design-basis" analysis is performed using more realistic analysis methods and assumptions and allows credit to be taken for non-safety SSCs and operator actions. In addition, more realistically conservative criteria are applied than those used in design basis analyses. Section 6.3 provides guidance on an appropriate set of modifications to the analysis methods and assumptions described in Sections 3, 4 and 5 for use in the Option B analysis to demonstrate mitigation capability.

Guidance is also provided in Section 7, addressing additional design considerations.

Figure 2-1
PWR Containment Recirculation Sump Performance
Evaluation Process Overview



3 BASELINE EVALUATION

3.1 INTRODUCTION

3.1.1 Purpose

The purpose of this baseline evaluation methodology is to provide licensees with a common and consistent approach for doing an initial scoping evaluation to evaluate the post-accident performance of the containment sump screen for a pressurized water reactor (PWR). This common and consistent method is termed the *"Baseline Evaluation Method."*

The Baseline Evaluation Method, and the guidance to perform the Baseline Evaluation Method, provides a conservative approach for evaluating the generation and transport of debris to the sump screen, and the resulting head loss across the sump screen. If a plant uses this method and guidance to determine that sufficient head loss margin exists for proper long-term Emergency Core Cooling (ECC) and Containment Spray (CS) function, no additional evaluation for head loss is required.

The same sumps may be used for both long-term ECC for heat removal from the core and long-term CS for heat removal from the containment environment. Revision 3 of Regulatory Guide 1.82 (Reference 1) refers to sumps performing this combined or dual function as Emergency Core Cooling (ECC) sumps. This convention of referring to dual-function sumps as ECC sumps will be used here.

3.1.2 Background

The probability of a high-energy line break (HELB) of PWR piping inside the Reactor Containment Building (containment) is extremely low. However, if the event were to occur, it could result in production of debris that, if transported to and deposited on the containment sump screens, could challenge the function of the ECC sumps. Specifically, debris that accumulated on the sump screens would result in an increase in the head loss across the resulting debris bed and sump screen. This head loss may be sufficiently large to exceed the available net positive suction head (NPSH) margin of the ECC sumps.

3.1.2.1 General Accident Scenarios of Concern

Postulated accident scenarios of concern are those that require the plant to initiate recirculation flow from the containment sump to mitigate the event. Therefore, the primary design basis accident (DBA) that could present a challenge to the ECC sumps is the loss-of-coolant-accident (LOCA). However, for some plants, a main steam line break or feedwater break could challenge ECC sump function as well.

3.1.2.2 Accident Phenomena

Three broad phenomena have been identified as governing post-accident sump performance:

1. Debris generation – The destruction of insulation and coatings, and erosion of concrete due to the action of the jet resulting from the postulated pipe break.

2. Debris transport – The movement of debris generated from the jet due to fluid movement and associated containment pooling and washdown of containment sprays, and from the erosion of submerged material, to the sump when the ECC and CS systems are realigned to draw suction from the containment sump.

3. Head loss – The development of resistance to flow across the ECC sump screen due to the transport and collection of debris on the sump screen.

The Baseline Evaluation Method provides guidance for licensees to address each of these phenomena and to address post-accident sump screen performance.

3.1.2.3 Limits of Evaluation Method

The guidance presented in the Baseline Evaluation Method only addresses the phenomena and issues up to and including head loss across the sump screen. The application of the Baseline Evaluation Method will provide information that can be used to assess resultant effects on NPSH or pump suction inventory. Insufficient information presently exists to evaluate the effects of chemical reaction products on head loss across a sump screen and associated debris bed. Guidelines will be provided when the data become available. Also, the Baseline Methodology does not include evaluation of holdup of flow by debris upstream of the sump screen, structural integrity of the sump screen, or the effects resulting from debris ingestion into the ECC or CS systems through the sump screen. See Section 7, “Additional Design Considerations,” for guidance on these topics.

3.1.2.4 Supplemental Guidance for Refinements to Baseline Evaluation

The Baseline Evaluation Method presented in this section provides one suggested approach for all utilities to perform an evaluation of the susceptibility of their ECC sumps to failure from debris-induced screen blockage. In addition to the Baseline Evaluation Method and supporting discussion, an example calculation applying the Baseline Method is provided. The guidance in this section provides a conservative approach for evaluating the generation and transport of debris, and the resulting head loss across the sump screen.

- If a plant uses this Baseline Evaluation Method and determines that head loss margin exists for proper ECC and CS function, no additional evaluation for head loss is required.

- If a plant determines that the results of the baseline approach are not acceptable, or additional design margin is desirable, the refinement guidance provided in subsequent sections may be used to further evaluate the post-accident performance of the ECC sump.

3.1.3 Data Collection to Support Baseline Evaluation

To perform the sump performance evaluation according to the guidance in this document, it is necessary to first gather the appropriate plant information. The information needed to support the baseline sump performance evaluation is similar to that needed to perform a containment condition assessment walkdown as described in NEI 02-01, "Condition Assessment Guidelines: Debris Sources Inside PWR Containments" (Reference 2). Therefore, the information primarily documents the configuration of containment and the potential debris sources contained therein.

The information required to perform the assessment can be categorized as follows:

1. General containment design information
    - Topographical containment layout drawings
    - Piping isometric drawings
    - Process diagrams
    - Accident analysis of record and associated licensing basis for post-LOCA recirculation including ECC and CS recirculation flows for various break sizes, spray sequence and flows, time duration, sump water temperature profile, etc.
2. Insulation details
    - Type(s) of insulation used inside containment (insulation specifications)
    - Volume of insulation material installed
    - Where it was used on equipment, in penetrations, on piping, etc. (drawings)
    - How it was installed; encapsulated, banded, etc. (drawings)
    - Inspection records, if appropriate or available
    - Design changes that may have changed insulation used (specifications and drawings)
3. Penetration details
    - Penetration plan (elevation and azimuth)
    - Drawings of insulation material used in penetrations
4. Fire barrier details
    - Type(s) of material used inside containment (material specifications)
    - Where it was used inside containment (drawings)
    - How it was installed (drawings)
    - Inspection records, if appropriate or available

- Design changes that may have changed fire barrier material or location inside containment (specifications and drawings)

5. Protective coatings details

   - What coatings were applied
   - Where they were applied
   - QA program requirements
   - Coatings application specification(s)
   - Coatings inspection records
   - Coatings that were applied to purchased equipment and the coatings program used to apply them
   - A copy of the "Exempt" or "Unqualified" coatings log, if used at the site

6. Other potential debris sources

   - Foreign materials exclusion program documentation
   - Latent debris observed to be inside containment
   - Tagging and labeling procedures or technical instructions
   - References for use of cable ties inside containment

The above listing of information is intended to be as complete as possible to support a plant-specific baseline evaluation. However, plant-specific features may suggest that additional information should be collected and supporting documents reviewed to support performance of the baseline evaluation.

3.2 METHOD OVERVIEW

The Baseline Methodology utilizes a conservative analytical approach to evaluating the five main topics associated with post-accident sump performance:

1. Break selection
2. Debris generation
3. Latent debris
4. Debris transport
5. Head loss

The approach taken in each of these topical areas for the Baseline Methodology is described in the following sections.

3.3 BREAK SELECTION

Discussed in this section are the considerations and guidance for selecting an appropriate postulated break size and evaluating the location of the postulated break that presents the greatest challenge to post-accident sump performance.

3.3.1 Introduction

The break selection is the first step in assessing post-accident sump screen performance. Break selection consists of two considerations:

1. The size of the break
2. The location of the break

The objective of the break selection process is to identify the break size and location that result in debris generation that is determined to produce the maximum head loss across the sump screen. Since this location is not known prior to performing the evaluation, the term break selection refers to a process of evaluating a number of break locations for a given size break to identify the location that presents the greatest challenge to post-accident sump performance.

3.3.2 Discussion

The objective of the break selection process is to evaluate and identify the break locations that provide for the following two results:

1. The maximum amount of debris that is transported to the sump screen
2. The worst combination of debris mixes that are transported to the sump screen

The locations that provide for these conditions are identified as "limiting break locations" in evaluating post-accident sump screen performance.

The criterion used to define the limiting break location is the head loss across the sump screen resulting from deposition of debris on the sump screen; the limiting break location results in the maximum head loss. As noted above, the limiting break location is not known prior to performing the evaluation, but is determined by evaluating a number of postulated break locations. To perform this evaluation, it is necessary to perform the debris generation, debris transport, and head loss calculations for each postulated break location. Therefore, the selection of the limiting break site is an iterative process that requires rigor.

The guidance below documents the process for determining the limiting break location.

3.3.3 Postulated Break Size

A double-ended guillotine break (DEGB) of piping, including the primary system piping, may be used as the postulated break size. This approach provides for the prediction of large volumes of debris from insulation and other materials that may be within the region affected by the fluid escaping through the postulated break. NRC has accepted this as an acceptable approach in the resolution of ECCS strainer blockage concerns for boiling water reactor (BWR) plants. This method is applicable to all PWR designs.

Some plant designs require recirculation of containment spray for long-term containment cooling after a main feedwater line break or a main steam line break. Either the same considerations as for LOCA or the plant's current licensing basis for those breaks may be used for break selection and size characterization.

3.3.4 Identifying Break Locations

Postulation of the break location is somewhat more complex than postulation of the break size. All reactor coolant system (RCS) piping, and connected piping, must be considered in the evaluation. Since many break locations are to be considered, a wide range of results should be expected. Some plant designs require plants to eventually recirculate coolant from the sump for pipe ruptures other than a LOCA. If this is a part of the plant licensing basis, then these lines must also be considered when identifying break locations.

3.3.4.1 General Guidance

It is recommended that pipe break locations considered be postulated based on the following criteria:

1. For postulated LOCAs, break exclusion zones are disregarded for this evaluation. In other words, pipe breaks must be postulated in pre-existing break exclusion zones. For main steam and feedwater line breaks, licensees should evaluate the licensing basis and include potential break locations in the evaluation, if necessary.

2. NRC Branch Technical Position MEB 3-1 shall not be used as a basis for determining potential LOCA break locations. The purpose of the analysis is to determine the worst possible break with respect to ECCS sump concerns. Therefore, the location of the pipe break is not chosen based on the stress distribution or fatigue characteristics of the piping system.

3. For plants for which main steam line breaks and/or feedwater line breaks must be considered, the break locations should be consistent with the plant's current licensing basis.

4. Pipe breaks shall be postulated at such locations that each location results in a unique debris source term (i.e., multiple identical locations need not be examined).

5. Pipe breaks shall be postulated in locations containing high concentrations of problematic insulation (microporous insulation, calcium-silicate, fire barrier material, etc.)

6. Pipe breaks shall be postulated with the goal of creating the largest quantity of debris and/or the worst-case combination of debris types.

7. Piping attached to the RCS that is small (< 2 inches in diameter) need not be considered. Breaks of this size are sufficiently small (and bounded by the larger breaks) that quantities of debris large enough to challenge the post-accident operability of the containment sump are not generated.

3.3.4.2 Piping Runs to Consider

As a minimum, LOCA breaks in the following lines should be considered:

1. Hot leg, cold leg, intermediate (crossover) leg and surge line.

2. Piping attached to the RCS. Examples include, but are not limited to charging lines and RHR lines.

Some plant designs require plants to eventually recirculate containment coolant from the sump for pipe ruptures other than a LOCA. Two such events are main feedwater breaks and steam line breaks. If this is a part of the licensing design basis for the plant under consideration, then these lines must also be considered for this evaluation.

3.3.4.3 Other Considerations for Selecting Break Locations

Subsection 3.3.2, "Discussion," identified the objective of break selection as of identifying a limiting break for post-accident sump performance consideration. Listed below are additional guidelines to use in selecting break locations that support that objective.

1. Locations are determined by considering the location of materials (insulation, coatings, etc,) inside containment relative to the break location and zone of influence (ZOI). Specifically, look for locations where problematic insulation (for example, microporous insulation) may be combined with particulate debris. Note that the location of materials inside containment should have been identified during the application of NEI-02-01 (Reference 2).

2. Identify locations for which postulated breaks generate an amount of fibrous debris that, after transport to the sump screen, creates a uniform fibrous bed of equal to or greater than 1/8-inch layer to filter particulate debris.

3. If the insulation does not result in the generation of significant particulate debris (for example, the insulation in the ZOI is RMI, there is no microporous insulation inside containment, and fibrous insulation is not affected by the postulated break), particular attention should be given to the characterization of latent debris sources as this source may present the limiting debris loading condition with respect to either fiber, particulates, or both.

3.3.4.4 Selecting the Initial Break Location

To start the break selection evaluation, select an initial break location using the guidance given in subsections 3.3.4.1 to 3.3.4.3. Multiple breaks will be examined to demonstrate that the limiting break location was considered. However, using the guidance identified in these sections, it is possible to identify locations that may be considered to be likely candidates for the limiting location. Thus, it is suggested that an initial postulated break location be chosen with the following characteristics:

1. Pick the initial break location to be near a large quantity of potential debris and/or near a combination of potential debris types that are known to challenge post-accident sump operation. It is suggested that results from a containment condition assessment, similar to that described in NEI 02-01 (Reference 2) would be useful in assessing such locations.

2. The location is a convenient place to start a sequence of breaks (e.g., at the physical end of a length of pipe when multiple locations on that length of pipe are being evaluated).

Given the above, it is suggested that a candidate location for the initial break location is the junction of the primary piping and the steam generator. Two general industry observations support this suggestion:

1. As a consequence of their size, steam generators have a larger volume of insulation applied to them than does primary system piping.

2. It has been observed that steam generators often have several different types of insulation applied to them.

Therefore, the selection of a break location at the junction of primary piping and the steam generator is a reasonable starting point to address the criteria of evaluating both the maximum amount of debris that is transported to the sump screen, and the worst combination of debris mixes that are transported to the sump screen.

3.3.5 Evaluation of Break Consequences

The evaluation of break consequences is the determination of the head loss across the sump screen as a result of the generation, transport, and accumulation of debris on the sump screen that is calculated to occur as a result of the postulated break, and the consequential head loss across the sump screen as emergency core cooling and containment spray recirculation water passes through the debris bed.

3.3.5.1 Purpose of Break Consequence Evaluation

The purpose of evaluating the consequences of a postulated break is to determine the head loss associated with that break and its effect on available NPSH for the recirculation pumps. To accomplish this, the following additional evaluations must be performed for each break location considered:

1. Evaluation of the zone of influence (ZOI), the region inside containment that is affected by the fluid escaping from the postulated break location, resulting in the generation of debris. As the ZOI is moved about to different break locations, robust structures (walls) may affect the geometry of the ZOI.

2. Evaluation of the debris source term.

3. Evaluation of debris transport to the sump screen.

4. Evaluation of head loss across the sump screen resulting from debris that has been transported to and deposited on the containment sump screen.

Evaluating break consequences in this way provides for the evaluation of sump screen head loss as a function of postulated break size and break location.

3.3.5.2 Selection of Intervals for Additional Break Locations

After evaluating the initial break location, additional locations are evaluated and the results compared, to determine the limiting location for the break size used.

For primary piping, it is suggested that the break location be moved at 3-foot increments along the pipe being considered. This break frequency provides for an acceptable determination of the limiting break location with respect to:

1. The maximum volume of debris that may be generated and transported to the sump screen.

2. The worst combination of debris that may be generated and transported to the sump screen.

It is expected that, as the plant-specific analysis develops, it will be determined and documented by inspection that the number of cases requiring detailed analysis can be limited based on debris inventory, similarity of transport paths, and piping physical characteristics.

The same strategies need not be applied when considering main steam line or feedwater line breaks. A sufficient number of breaks, consistent with the plant-specific design and licensing basis, should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris.

For attached piping, only the length of pipe run up to the flow isolation point need be considered. This approach will account for debris generation from postulated pipe breaks, including single-sided breaks, from attached piping. There is no need to consider pipe breaks in attached piping beyond the isolation points since such breaks, should they occur, will not result in the plant evolving to recirculation from the containment sump to mitigate the event.

3.4 DEBRIS GENERATION

3.4.1 Introduction

Following identification of postulated break locations, the next step taken in evaluating post-accident sump performance is to determine an appropriate zone of influence (ZOI) within which the resultant break jet would have sufficient energy to generate debris. It is noted that not all debris that is evaluated to be generated is in a form that may be transported to the sump. Thus, evaluation of debris generation from a postulated break is a two-step process:

1. Evaluate an appropriate ZOI in which debris is generated.
2. Evaluate the characteristics of the debris generated.

Included in this second step is the identification of transport characteristics of the debris generated by the postulated break. Thus, the evaluation of debris generation for a given break location is an exercise of establishing the appropriate size and shape of the ZOI, mapping that ZOI volume over the spatial layout of insulated piping, and calculating the volume of insulation within that ZOI. The final step to evaluating debris generation is the application of a size distribution to the debris generated within the ZOI volume that will be used to evaluate debris transport.

The identification of the ZOI and resulting debris generation for postulated pipe breaks (LOCA, main steam line or feedwater) is both plant- and break-specific. Presented in this section is guidance in establishing the appropriate ZOI and resulting debris characteristics for LOCA. This guidance is also applicable to postulated main steam line and feedwater line breaks

3.4.2 Zone of Influence

The zone of influence is defined as the volume about the break in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, and other materials within the zone. For the baseline calculation, it is recommended that the boundary of the ZOI be assumed to be spherical, with the center of the sphere located at the break site. The use of a spherical ZOI is intended to encompass the effects of jet expansion resulting from impingement on structures and components. Use the guidance in subsections 3.4.2.1 and 3.4.2.2 to determine the ZOI for a postulated pipe break.

Guidance on the identification of other, more realistic ZOIs is given in Section 4.

3.4.2.1 Recommended Size of Zone of Influence

To determine the radius of the spherical ZOI needed to represent the effects of the jet originating from a postulated pipe break, the ANSI/ANS 58.2-1988 standard (Reference 3, Section 3.2.7) was used. Appendices B, C, and D of Reference 3 provide the guidance necessary to determine the geometry of a freely expanding jet. Guidance is provided for jets originating from a variety of reservoir conditions, including subcooled conditions.

The guidance in Reference 3 was used to determine the geometry of a jet originating from a postulated break in a PWR piping system. A subcooled reservoir and flashing break flow were assumed for the calculations as detailed below. The following steps were followed in performing the calculations:

1. The mass flux from the postulated break was determined using the Henry-Fauske model, as recommended in Appendix B, for subcooled water blowdown through nozzles, based on a homogeneous non-equilibrium flow process. No irreversible losses were considered.

2. The initial and steady-state thrust forces were calculated based on the guidance in Appendix B of Reference 3, and the postulated reservoir conditions detailed below.

3. The jet outer boundary and regions were mapped using the guidance in Appendix C, Section 1.1 of Reference 3 for a circumferential break with full separation. The input to the equations from Appendix C for the thermodynamic conditions at the asymptotic plane was calculated using principles of thermodynamics and the postulated conditions in the reservoir.

4. A spectrum of isobars was mapped using the guidance in Appendix D of Reference 3. Several isobars were considered of interest, including the 10 psi isobar. The 10 psi isobar was of interest as NEDO-32686 (Reference 4) identifies 10 psi as the destruction pressure of jacketed Nukon insulation with standard bands or unjacketed Nukon.

5. The volume encompassed by the various isobars was calculated using a trapezoidal approximation to the integral. A study was performed to ensure that the results of the volume calculations are not sensitive to the resolution of the trapezoidal approximation. Since the volume result only represents the volume encompassed by the isobars in a free jet, the volume encompassed by results was doubled to represent the double-ended guillotine break (DEGB).

6. The radius of an equivalent sphere was calculated to encompass the same volume as twice the volume of a feely expanding jet calculated from step 5, above.

The radius calculated in step 6, above, is taken to be the radius of the ZOI that will be used to calculate the volume of debris generated from a postulated break.

The jet expansion calculations were based on the following conditions:

1. A circular break geometry was used for the calculations. This break geometry is representative of both a postulated DEGB of primary piping as well as the DEGB of piping attached to the RCS. The complete breaking of a pipe, either primary

piping or piping attached to the RCS, provides for a maximum debris generation volume as there are two ends of the break to release fluid.

2. Fluid reservoir conditions of 2250 psia and 540°F were used for the calculations. The corresponding stagnation enthalpy and subcooling used in the calculations are 547.2° Btu/lbm and 102.7°F, respectively. These conditions are intended to represent a PWR cold leg at full power and provide for a conservatively large ZOI compared to hot-leg conditions at power operations.

3. Ambient pressure of 14.7 psia was used. This is conservative since no credit is taken for containment backpressure (the increase in containment pressure that would result from the release of mass and energy into the containment as a result of the postulated break).

The ZOI is expressed as the ratio of the radius of the equivalent ZOI sphere to break size diameter. This allows the ZOI to be expressed independently of the break size.

The use of a spherical ZOI is conservative compared to jet impingement evaluations previously reviewed and approved by the NRC. It is noted that, for a number of plants, a 10D value is assumed for the limit of jet damage. This is based on NUREG/CR-2913, dated January 1983. As an example, the acceptability of this approach is documented in the Supplement 6 of the Watts Bar Safety Evaluation Report (SER):

> *The applicant has given the staff information requiring the analysis of jet impingement loads for postulated breaks. In FSAR section 3.6A.1.1.2, test data and analysis developed in NUREG/CR-2913, "Two Phase Jet Loads," dated January 1983, are used to establish the criterion that unprotected components located more than 10 diameters from a pipe break are without further analysis assumed undamaged by a jet of steam or subcooled liquid that flashes at the break. The staff has previously reviewed the methodology used in NUREG/CR-2913 for determining the effects of such a jet on components at a distance greater than 10 diameters and has found it acceptable.*

Protective Coatings

The criteria for DBA-qualification, or designation as "Acceptable," of protective coatings (paints) applied to systems, structures, and components in PWR containments do not provide data concerning coatings exposed to direct impingement of fluids. As such, the ZOI for DBA-qualified coatings or coatings determined to be "Acceptable," applied to PWR containment surfaces, which results from fluid impingement from the break jet, has not been clearly defined.

However, an extensive body of data exists related to removal of industrial protective coatings by high-pressure and ultra-high-pressure waterjetting. Examination of the data and associated industry standards, compiled since the mid-1980s, reveals that industrial protective coating systems, identical to the DBA-qualified and "Acceptable" coatings applied to systems, structures, and components in PWR containments, require a water jetting pressure of at least

7,000 psig to initiate destruction of sound coatings. This ability of coatings to withstand high and ultra-high pressure has been reviewed and documented in a paper prepared by a recognized industry coatings expert (Reference 5), included as Appendix A.

Based on evaluation presented, a destruction pressure of 1000 psi is chosen for coatings that meet DBA-qualified or "Acceptable" criteria. This is conservative for the following reasons:

1. The value of 1000 psi is seven to eight times lower than the pressures that have been observed in industrial practice to remove coatings using waterjet technology.

2. The initial RCS pressure of 2250 psi is about one-quarter of the pressures that have been observed in industrial practice to remove coatings using waterjet technology.

3. Industrial experience with waterjet technology to remove coatings requires application of the high-pressure jet at close proximity of the surface to which the coating is applied (< 12 inches from the jet nozzle discharge) for extended periods of time (> 60 seconds).

4. The blowdown of a PWR RCS due to a large LOCA is on the order of 30 seconds.

5. The break discharge pressure decreases over the duration of the blowdown period.

Thus, it is concluded that the use of a value of 1000 psi as the destruction pressure for DBA-qualified and "Acceptable" protective coatings is both appropriate and conservative. The recommended ZOI to be used to evaluate protective coatings debris for the baseline containment sump evaluation is listed in Table 3-1.

This same industrial experience suggests that the mechanism of coating removal by waterjets is erosion. The observed coating debris sizes are in the range of 10 microns to 50 microns, not flakes or chips. Thus, it is recommended that the coating debris generated within the ZOI representing 1000 psi be treated as fine particulate debris. It is further recommended that this coating debris be considered highly transportable.

3.4.2.2 Selecting a Zone of Influence

For the baseline calculation, the ZOI for a break is selected based on the potentially affected insulation inside containment with the minimum destruction pressure. This ZOI is then applied to all insulation types. As discussed in the previous section, this approach provides for the calculation of a conservatively large value for debris generation.

Table 3-1. ZOI Radii for Common PWR Insulation and Coatings Materials

Insulation Types	Destruction Pressure (psi)	ZOI Radius/Break Diameter	
		Calculated Value	Recommended Value
Protective Coatings (epoxy and epoxy-phenolic paints)	1000 (Ref. 5)	0.24	1.0
Protective Coatings (untopcoated inorganic zinc)	333 (Ref. 5)	0.55	1.0
Transco RMI Darchem DARMET	190 (Ref. 6)	1.11	1.3
Jacketed Nukon with Sure-hold® bands Mirror® with Sure-Hold® bands	150 (Ref. 6)	1.51	1.6
K-wool	40 (Ref. 6)	3.73	3.8
Cal-Sil (Al. cladding, SS bands)	24 (Ref. 7)	5.45	5.5
Temp-Mat with stainless steel wire retainer	17 (Ref. 6)	7.72	7.8
Unjacketed Nukon, Jacketed Nukon with standard bands Knaupf	10 (Ref. 6)	12.07	12.1
Koolphen-K	6 (Ref. 6)	16.97	17.0
Min-K Mirror® with standard bands	4 (Ref. 6)	21.53	21.6

3.4.2.3 The ZOI and Robust Barriers

For a given break location, the boundary of the spherical ZOI is drawn about the break. It is possible that this boundary will extend beyond robust barriers such as walls and components. Such barriers will terminate further expansion of the ZOI.

1. In the case of a wall, the sphere will be truncated at the intersection of the sphere and wall.

2. For a component or structural components such as supports, a pressurizer, steam generator, reactor coolant pump or jet shields, the area in the shadow of the component or structure will be free from damage.

There is sufficient conservatism in drawing the sphere that it is not reasonable that a jet reflected off of a wall or structure would extend further than the unrestrained sphere. Furthermore, there are precedents for this conclusion in the BWROG URG. When evaluating targets for jet impingement, jets were terminated when a robust barrier was encountered. Reflected jets were not considered as they were bounded by the conservatism in the approach taken.

3.4.2.4 Simplifying the Determination of the ZOI

Given the complexity of the analysis as a whole, it may be desired to make conservative assumptions with the goal of simplifying the analysis. For example, for some breaks it may be only slightly more conservative and much simpler to assume that an entire subcompartment (but not outside the subcompartment) becomes the ZOI.

Once the boundary of the ZOI has been defined, proceed with determining the amount of debris that is generated within the ZOI.

3.4.2.5 Evaluating Debris Generation within the ZOI

Once the ZOI has been determined, calculate the amount of debris generated within the ZOI. Information about the type, location, and amount of debris sources within the containment is obtained from plant drawings and the results of a condition assessment walkdown such as described in NEI 02-01 (Reference 2). The characterization of the debris (transport characteristics) is evaluated using the guidance of the following section.

3.4.2.6 Sample Calculation

The following is a sample calculation of a ZOI and the debris that would be generated within that ZOI.

1. For the sample calculation, a single break size and break location will be assumed and evaluated.

2. The break will be assumed to be at the base of the steam generator[1] The reason for this choice is that often, more than one type of insulation is applied to steam generators. Figure 3-1 shows a sample schematic of a reactor coolant system.

3. It will also be assumed that walkdown data for the plant are available and documented in sufficient detail to support this evaluation. For the purposes of this evaluation, it will be assumed that the walkdown was performed by dividing the containment into zones and recording the amount of insulation in each zone. The debris generation zones defined from the walkdown are also shown in Figure 3-1 and are labeled as Zone A1, Zone A2, etc. Note that the plant layout and engineering judgment are used to define the zones used to record the location of insulation inside containment.

---

1 A 10-inch break is an idealization for the steam generator. It is used here to illustrate the calculation method.

4. The postulated break will be assumed to occur in Zone A4. For this sample calculation, it is assumed that the walkdown records show the amount of insulation in Zone A4 to be:

    - 300 ft^3 of Nukon insulation
    - 15,000 ft^2 of RMI

5. A 10-inch break of piping attached to the RCS is assumed. The corresponding ZOI is evaluated as follows:

    The diameter of the break is taken as:

    $$D_{BREAK} = 10 \text{ inches}$$

    Using the criteria identified above, the minimum destruction pressure for insulation is used to determine the ZOI. From Table 3-1, the recommended ratio of ZOI radius to break diameter is:

    $$\frac{r_{ZOI}}{D_{BREAK}} = 12$$

    The radius of the spherical ZOI is calculated as:

    $$r_{ZOI} = D_{BREAK} \text{ x } \frac{r_{ZOI}}{D_{BREAK}} = 10 \text{ inches x } 12 = 120 \text{ inches} = 10 \text{ ft}$$

    Thus, the radius of the ZOI is determined to be 10 feet. This ZOI is conservatively applied to all insulation types in the region within the ZOI for the baseline evaluation.

6. A ZOI having a 10 foot radius is superimposed at the base of the steam generator in Zone A4 of Figure 3-1. From the figure, it is observed that the ZOI includes a substantial portion of the steam generator and associated reactor coolant system piping within Zone A4. Insulation is applied to these components. Therefore, for this sample calculation, a ZOI with a radius of 10 feet is conservatively evaluated to result in the destruction of all the insulation within Zone A4. This results in the following volumes of insulation debris:

    - 300 ft^3 of Nukon insulation
    - 15,000 ft^2 of RMI.

7. Using the recommended ratio of ZOI radius to break diameter for coatings of 1.0 that is given in Table 3-1, the radius of the coatings ZOI is evaluated as:

$$r_{ZOI} = D_{BREAK} \text{ x } \frac{r_{ZOI}}{D_{BREAK}} = 10 \text{ inches x } 1.0 = 10 \text{ inches} = 0.833 \text{ ft}$$

From Figure 3-1, it is clearly observed that the coating ZOI will not be in contact with either walls or floors. Furthermore, with a small ZOI for coatings, coated structures or components may not be within the ZOI. However, a conservative estimate of the square footage of coatings debris is estimated by using the surface area of the sphere of the coatings ZOI:

$$A_{\text{COATINGS DEBRIS}} = 4\pi\, r^2 = 4\pi\,(0.833)^2 = 8.72 \text{ sq. ft}$$

Thus, the amount of coating debris generated by the postulated 10-inch break is conservatively estimated to be 8.72 ft^2.

The transport characteristics of the debris volumes calculated above are evaluated using the guidance of the following section. The transport of the debris evaluated using the guidance of Section 3.6, and the resulting head loss evaluated using the guidance of Section 3.7. The debris generation evaluation is repeated using the guidance of Section 3.3 until the limiting head loss is evaluated.

3.4.3 Quantification of Debris Characteristics

3.4.3.1 Definition

Debris characteristics are:

- The post-accident (LOCA and/or secondary pipe breaks where applicable) size distribution of a material.

- The debris material size and shape as well as the micro-density (i.e., material density) and macro-density (i.e., as-fabricated density).

Debris characteristics are used in transport and head loss calculations. The debris generation section provides the following items as inputs to this section:

- The volume of insulation material in a ZOI.
- The surface area of the ZOI for coatings.
- The total quantity of indeterminate[2] and unqualified coatings inside containment.
- The total quantities of indeterminate and unqualified coatings that have been applied to piping that are covered by undamaged insulation.

2 For definitions of DBA-qualified/acceptable, DBA-unqualified/unacceptable, and indeterminate coatings, see ASTM D-5144-00, “Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants.”

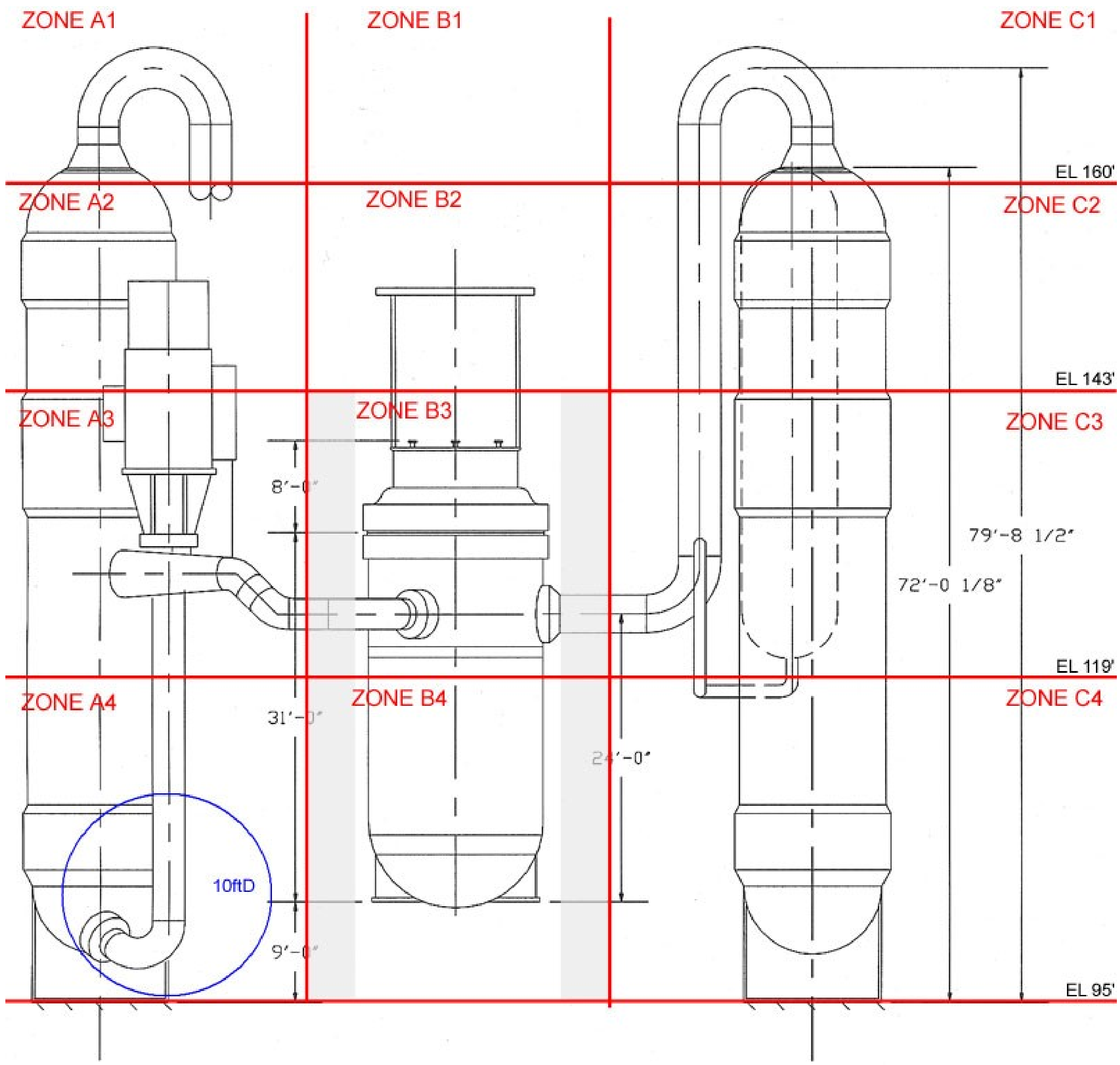


Figure 3-1. Schematic Showing Reactor Coolant System and Walkdown Zones

3.4.3.2 Discussion

The first-order debris characteristic is the size distribution of the material inside ZOI of a postulated pipe break. Following a postulated pipe break, all material inside containment may also be subjected to containment spray or immersed in the post-accident pool, and additional debris would be generated; therefore, the characteristics of the debris generated post-blowdown also need to be identified.

There have been numerous schemes developed for classifying debris size distribution of material inside a ZOI. Most of the classification schemes developed were for low-density fiberglass blankets manufactured by Performance Contracting Inc. (PCI) and Transco. NUREG/CR-6369 (Reference 16) employs five fibrous debris size classification schemes, with three to six size designations (e.g., large, medium, and small). NUREG/CR-6224 (Reference 17) adopts a classification scheme of seven size categories for fiber. As noted in NUREG/CR-6369, the BWROG URG adopted a fiber classification scheme of two sizes: fines and large.

The Air Jet Impact Tests (AJITs) conducted by the BWROG indicated a dependence of the size distribution of the debris on distance from the nozzle, i.e., the higher the pressure, the larger the quantity of small debris. As discussed in NUREG/CR-6808 (Reference 6), Section 3.3, an analytical model could be applied that correlates the size distribution to the spherical ZOI. This type of modeling requires the understanding of the damage distribution based on applicable experimental data. Unfortunately, there is a paucity of applicable debris generation test data applicable for PWR conditions. In the absence of directly applicable experimental data, i.e., tests conducted with prototypical PWR conditions, for a wide variety of material, the NEI Guideline adopts a two-size distribution for material inside the ZOI of a postulated break: small fines and large pieces. Small fines will be defined as any material that could transport through gratings, trash racks, or radiological protection fences by blowdown, containment sprays, or post-accident pool flows. Furthermore, the small fines are assumed to be the basic constituent of the material for fibrous blankets (i.e., individual fibers) and pigments for coatings. This guideline assumes the largest openings of the gratings, trash racks, or radiological protection fences to be less than a nominal 4 inches by 4 inches (less than 20 square inches total open area). The remaining material that cannot pass through gratings, trash racks, and radiological protection fences is classified as large pieces.

Some material in the post-DBA environment will be eroded by the water flows. Additionally, some debris material may be disintegrated by the water flow. The classification for fibrous material in the ZOI adopted by this guidance assumes that all fibrous materials classified as small fines are essentially reduced to the individual fibers. As such, the debris classification implicitly considers the erosion and disintegration of the debris by conservatively assuming that they are already of a characteristic size that cannot be further decreased by erosion or disintegration. For fibrous insulation material, the large pieces are assumed to be jacketed or canvassed. According to NUREG/CR-6369, jacketed pieces are not subjected to further erosion. The same conservatism was applied for coatings in the ZOI where this guideline assumes that all coatings in the coating ZOI are considered to be small fines of the size of the original pigment, hence not capable of being subjected to erosion or disintegration. For material outside the ZOI, all insulation material that is jacketed is assumed not to undergo erosion or disintegration by containment spray or break flow. This assumption is based also on NUREG/CR-6369 tests that showed no erosion of damaged jacketed material, hence the same applies to undamaged jacketed material. Additionally, PCI has conducted tests on undamaged Nukon blankets to demonstrate that they are not subject to erosion in a post-DBA environment. The NRC issued a Safety Evaluation Report (SER) on the tests accepting the PCI test results.

The main source of data on debris size distribution of material subjected to simulated pipe break conditions is that reported in the BWROG URG AJIT tests and the NRC debris transport set of experiments described in NUREG/CR-6339. This NEI Guideline selected the test of the insulation that had the most data points (Nukon) that produced the smallest fines and adopted this point as the bounding value of fines production for unjacketed fibrous blankets. The data of size distribution following exposure to simulation of a pipe break close to PWR prototypical conditions are depicted in Table 3-7 of NUREG/CR-6808 for a low-density fiberglass tested at Ontario Power Generation. That test indicates that 52 percent were of the category defined as small fines adopted by this guideline. This test suggests that the size distribution for Nukon blankets in this guideline is conservative for PWR applications. For fibrous insulation materials that underwent testing at AJIT, this guideline adopted the Nukon blanket size distribution for fibrous blankets whose destruction pressure was the same or higher than for Nukon blankets. If a material has a higher destruction pressure, it signifies that the material has a higher resistance to damage. As such, the size distribution would tend to be larger than a more fragile material indicated by a lower destruction pressure. Therefore it is conservative to adopt the Nukon blanket size distribution for material with a higher destruction pressure. For material with an equivalent destruction pressure as Nukon blankets, engineering judgment suggests that the fraction of fines should be no worse than for Nukon blankets.

The calculation of the quantities for each size category for each of the materials entails multiplying the volume of each material calculated to be in the ZOI by the percentage of the two-size distribution recommended below.

3.4.3.3 Size Distribution

3.4.3.3.1 Fibrous Material in a ZOI

The fibrous classification of "small fines" adopted in this guideline can be correlated to the combination of "small" and "medium" classification of Table 3-7 of NUREG/CR-6369, Vol. 2; the combination of "small" and "large" classification of Table 2-5 of NUREG/CR-6369, Vol. 1; Classes 1-6 of NUREG/CR-6224; and the combination of "Fines" and "Large" classification of the BWROG URG AJIT. The classification of "large pieces" adopted in this guideline can be correlated to the large category of Table 3-7 of NUREG/CR-6369, Vol. 2; the "large canvassed" of Table 2-5 of NUREG/CR-6369, Vol. 1; Class 7 and "non-transportable" of NUREG/CR-6224; and the combination of "canvas" of the BWROG URG AJIT.

The following are the material-specific size distribution values adopted by this guideline:

1. <u>Nukon fiber blankets.</u> This guideline adopts the value of 60 percent for small fines and 40 percent for large pieces as the size distribution of Nukon (jacketed or

unjacketed) inside a pipe break ZOI. As noted previously, these values were selected from the BWROG URG AJIT of Nukon that generated the largest quantity of small fines and is considered to be applicable to PWR conditions based on the Ontario Power Generation test reported in NUREG/CR-6808.

2. Transco fiber blankets. This guideline adopts the value of 60 percent for small fines and 40 percent for large pieces as the size distribution of Nukon inside a pipe break ZOI. Transco blankets were not tested by the BWROG at the CEESI AJIT facility. Transco blankets were used, however, by the NRC at the CEESI AJIT facility as documented in NUREG/CR-6369. The study shows that the Transco blankets tested behaved similarly to the Nukon. Given these experimental data, engineering judgment suggests that Transco low-density fiberglass blankets would behave similarly to the Nukon fiberglass blankets when subjected to prototypical PWR DEGB DBA conditions, hence the size distribution adopted for Transco fiberglass blankets in this guideline is conservative since the size distribution adopted for Nukon fiberglass blankets was the most conservative size distribution of any of the AJIT tests of Nukon fiberglass blankets.

3. Knaupf. Knaupf was tested by the BWROG at the CEESI AJIT facility and shown to have the same destruction pressure as Nukon. Therefore, engineering judgment suggests that the size distribution should be no worse than Nukon. Hence, this guideline adopts the same size distribution for Knaupf as Nukon: 60 percent for small fines and 40 percent for large pieces.

4. Temp-Mat. Temp-Mat was tested by the BWROG at the CEESI AJIT facility and shown to have a higher destruction pressure than Nukon. Therefore, engineering judgment suggests that the size distribution should be no worse than Nukon. Hence, this guideline adopts the same size distribution for Knaupf as Nukon: 60 percent for small fines and 40 percent for large pieces.

5. K-Wool. K-Wool was tested by the BWROG at the CEESI AJIT facility and shown to have a higher destruction pressure than Nukon. Therefore, engineering judgment suggests that the size distribution should be no worse than Nukon. Hence, this guideline adopts the same size distribution for K-Wool as Nukon: 60 percent for small fines and 40 percent for large pieces.

6. Min-K. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for Min-K in a ZOI.

7. Generic low-density fiberglass. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for generic fiberglass in a ZOI.

8. Generic high-density fiberglass. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for generic high-density fiberglass in a ZOI.

9. Generic mineral wool. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for any type of mineral wool in a ZOI.

3.4.3.3.2 Reflective Metallic Insulation (RMI) in a ZOI

The NEI guideline adopts one size distribution classification scheme for all types of RMI insulation after exposure to the conditions within a PWR ZOI, since their ensuing transport and head loss guidelines do not differentiate between different types of RMI (i.e., stainless steel or aluminum).

RMI. The NEI guideline adopts the value of 75 percent for small fines and 25 percent for large pieces as the size distribution of any type of RMI inside a pipe break ZOI. These values are based on the size distribution of less than 4 inches as listed in Figure 3-7 of NUREG/CR-6808 based on the two-phase testing of a Diamond Power RMI cassette. The size of 4 inches was selected as a conservative upper bound of an RMI debris size that would go through gratings, trash racks, or radiological protection fences by blowdown, containment sprays, or post-accident pool flows. BWROG URG AJITs of other types of RMI suggests a significantly larger destruction pressure and a consequently smaller quantity of small size debris. Engineering judgment suggests that the 75 percent adopted for the RMI small-size category in this guideline is conservative in that it is based on the test that resulted in the largest quantity of small RMI debris for a type of RMI that has the lowest AJIT destruction pressure.

3.4.3.3.3 Other Material in ZOI

1. Calcium silicate. There is a wide variety of calcium silicate type insulation installed in PWRs. Some include fiberglass fibers as reinforcement, others use organic fibers, and some of the Cal-Sil used up to the late 1950s used asbestos fibers. The Cal-Sil solubility also varies by manufacturer, with some Cal-Sil dissolving promptly in hot water, whereas some dissolves at a significantly lower rate. The only publicly available size distribution data on the reaction of an unspecified Cal-Sil to a two-phase jet are found in Table 3-6 of NUREG/CR-6808. Test 5 indicated that the size categories adopted by this guideline would be 50 percent for small fines and 50 percent for large Cal-Sil pieces. Given the uncertainties in the subsequent erosion by the post-DBA water, this guideline assumes that 100 percent of Cal-Sil in a ZOI is destroyed as small fines.

2. Microtherm. Absent applicable experimental data or qualification documentation, a value of 100 percent small fines is adopted by this guideline for Microtherm in a ZOI.

3. Koolphen. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for Koolphen in a ZOI.

4. Fire barrier. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for all types of fire barrier material in a ZOI.

5. Lead wool. Absent applicable experimental data, a value of 100 percent small fines is adopted by this guideline for all types of lead wool material in a ZOI.

6. Coatings. All coatings within the coatings ZOI are considered in this guideline to fail when subjected to DBA conditions. Guidance concerning the determination of the Coatings ZOI is contained in Appendix A. Absent applicable experimental data, a coating debris size value of 100 percent small fines (10 µm IOZ equivalent) is adopted by this guideline for all types of coating material in the ZOI.

3.4.3.3.4 Material Outside the ZOI

Material outside the ZOI can be subjected to containment spray and/or be immersed in the post-DBA pool. Under these circumstances, some material could become debris and become subject to transport to the sump screen. Material and components that meet equipment qualification requirements (i.e., material and components on the Environmental Qualification list) have been demonstrated not to degrade in a post-DBA environment so they will not contribute to the post-DBA debris load.

1. Covered (jacketed) undamaged insulation. Nukon blankets are EQ-qualified and as such will not be damaged by the post-DBA environment outside the ZOI. The scant publicly available data for reaction of jacketed fibrous insulation material to post-DBA conditions that exist come from the NRC. The NRC tests were performed on low-density fiber (Transco blankets) and reported in NUREG/CR-6369, Volume 1. Both series of tests were conducted with pieces of blankets that had been subjected to the air jet impact tests at the AJIT facility. No intact blankets were tested. NUREG/CR-6369 concluded that partially torn insulation blankets that retained their cover were unlikely to be eroded by water flow from washdown and spray. Based on these tests and the EQ of Nukon blankets, this guideline adopts the position that covered (jacketed) undamaged insulation material outside the ZOI will not generate transportable debris. (Covered or jacketed insulation is any insulation in which the raw material, e.g., fiberglass bats, is covered or encapsulated by another material).

2. Other material outside the ZOI.

   - Fire barrier. Applying the same logic as was concluded in NUREG/CR-6339 for partially torn insulation that retained their wrappings/covers/jackets, all jacketed covered, or wrapped fire barriers are presumed not to degrade in the post-accident environment, and hence not generate debris. Fire barrier materials that are not jacketed, wrapped, or covered are presumed to fail as small fines.

   - Lead wool. The lead wool blankets have the same general covers as the Nukon and Transco blankets. As such, the conclusions of the NRC experiments are applicable. The NEI Guideline considers that all lead wool blankets outside the ZOI will not be damaged by the post-DBA environment.

- Unjacketed insulation. All materials outside the ZOI that are unjacketed, e.g., fiberglass bats without any covering, are presumed to fail to small fines.

- Coatings. DBA-qualified and acceptable coatings[3] located outside the coatings ZOI are considered in this guideline not to fail when subjected to containment spray or immersed in the post-DBA pool. All indeterminate and DBA-unqualified and unacceptable coatings are considered in this guideline to fail. This baseline guideline considers all indeterminate and DBA-unqualified and unacceptable coatings as a single category of coating, producing debris of the same characteristic independent of the type of coating, when subjected to containment spray or immersed in the post-DBA pool. All types of coatings on piping or components covered with undamaged insulation are considered in this guideline not to contribute to the post-DBA debris source term.

3.4.3.4 Calculate Quantities of Each Size Distribution

The total quantity of each size distribution for each material is the summation of the size distribution for the debris size quantity in the ZOI added to the debris size quantity outside the ZOI. To calculate the quantity of debris size for a material[4], the process is:

1. To obtain the quantity of small fines, multiply the volume of a material in the ZOI computed in the debris generation section by the recommended value of the small size percentage.

2. To obtain the quantity of large pieces, multiply the volume of a material in the ZOI computed in the debris generation section by the recommended value of the large size percentage.

3. Recent surveys of U.S. PWR containments per NEI 02-01 have determined that the majority of the coatings on structures, systems, and components within containment can be classified into three major categories:

   a. Inorganic zinc primers
   b. Epoxy primers and topcoats
   c. Epoxy phenolic primers and topcoats

   Plant-specific information should be used to estimate the thickness of the coatings. For those plants that do not have detailed plant-specific information, the following guidance is provided. For coatings within the ZOI, multiply the area of the coating ZOI as determined in the debris generation section by the thickness of the coating

3 For definitions of DBA-qualified/acceptable, DBA-unqualified/unacceptable, and indeterminate coatings, see ASTM D5144-00, "Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants."

4 Plant-specific information size distribution based on qualification testing should be used in lieu of the general recommendation of the NEI Guideline.

system: 3 mils inorganic zinc primer plus 6 mils epoxy/epoxy phenolic topcoat[5] to obtain the quantity (volume) of coating debris small fines from a ZOI. Coatings within the ZOI will be reduced, worst case, post-DBA to small (10 µm[6]), pigment-sized particles (see Table 3-3).

To obtain the quantity (volume) of coating debris outside the ZOI, multiply the total area of DBA-unqualified/unacceptable and indeterminate coatings[7] in containment by the worst case of 3 mils inorganic zinc primer. Note that epoxy and epoxy phenolic coating failure outside the ZOI will result, in all likelihood, in debris that are relatively larger, highly cohesive, and no smaller in the worst case than 25 µm. Unfortunately, there are no applicable experimental data as to the size distribution of failed DBA-unqualified/unacceptable and indeterminate coatings when subjected to a post-DBA environment. As such, the assumption that an equivalent volume of inorganic zinc particulate debris (particle size 10 µm) is conservative.

3.4.3.5 Sample Calculation

Material in the ZOI:

- Total volume of Nukon blankets in ZOI: 300 ft^3
- Quantity of small fines of Nukon in the ZOI: 300 ft^3 * 60% = 180 ft^3
- Quantity of large pieces of Nukon in the ZOI: 300 ft^3 * 40% = 120 ft^3
- Total area of RMI material in ZOI: 15,000 ft^2
- Quantity of small fines of RMI in the ZOI: 15,000 ft^2 * 75% = 11,250 ft^2
- Quantity of large pieces of RMI in the ZOI: 15,000 sq ft * 25% = 3,750 ft^2

Coatings:

The baseline sample plant has not conducted a detailed containment coating walkdown. From the debris generation, the coating ZOI has a radius of 10 inches. The surface area of a 10-inch sphere is 8.7 ft^2. The total quantity of failed coatings from the ZOI can be calculated as: 8.7 ft^2 * 7.5 E-4 ft[8] = 0.007 ft^3 of IOZ equivalent debris.

From the plant Appendix R, the total quantity of coatings in containment is 190,000 ft^2. From the plant construction records a total of 160,000 ft^2 can be shown to be DBA qualified. Hence the total quantity of DBA-unqualified/unacceptable and indeterminate coatings is estimated to be

5 Typical dry-film thickness values for inorganic zinc primers and epoxy/epoxy phenolic primers and topcoats are taken from coating manufacturer's product data sheets (for instance, Carboline CZ 11, Carboline Phenoline 305 primer and finish, Ameron D-6, Ameron D-9, Ameron Amercoat 66) for coating products currently installed in U.S. PWR containments.

6 The 10-micron size is conservative (i.e., more transportable and causes higher head losses) than the larger sizes suggested in subsection 3.3.3 and Appendix A.

7 For definitions of DBA-unqualified/unacceptable and indeterminate coatings, see ASTM D5144-00, "Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants."

8 9 mils = 7.5 E-04 ft

30,000 ft^2. The total quantity of small fines coating from outside ZOI: (30,000 ft^2 of total quantity of unqualified and undetermined coating in containment less the 0 ft^2 of unqualified and undetermined coating on piping that is covered by undamaged insulation.) * 2.5E-4 ft[9] = 7.5 ft^3 of IOZ equivalent debris.

3.4.3.6 Debris Characteristics for Use in Debris Transport and Head Loss

The debris characteristics for the small fines size adopted by this guideline are those in the following tables labeled as characteristic size. The next sections describe the characteristics of common fibrous coatings and particulate debris.

The characteristic sizes listed are the most conservative values that can be associated with debris transport and head loss since they are the size that will have the highest transport factor and cause the highest head loss. Other small debris characteristic sizes can be adopted in lieu of those listed for materials that have applicable transport and head loss experimentally determined characteristic sizes. Plant-specific data can supersede these where necessary and appropriate.

Mass Insulation

This class of insulation includes low-density fiberglass (~2.4 lbm/ft^3), medium-density fiberglass, and preformed fiberglass, as well as fiber felt materials. It also includes microporous insulation such as MinK and Microtherm, as well as calcium silicate insulation.

There are three principal types of mass insulation in PWR containments:

- Fibrous insulation (including asbestos)
- Granular insulation (calcium silicate and microporous)
- Cellular insulation

The characteristic densities and sizes for thermal insulation materials that have been identified as potential debris in nuclear containments are listed in Table 3-2. Some are listed by trade names and some by generic names, whereas others are listed as a system and still others as simply an insulation material. For materials not listed, the manufacturer should be contacted to obtain the type of information listed in Table 3-2.

Fibrous insulation materials include fibrous glass wool such as Performance Contracting's Nukon, Transco Products' Thermal Wrap®, pre-formed fiberglass pipe (made by Owens-Corning, Knaupf, and Johns-Manville), and fiberglass pipe and tank wrap (from the same three manufacturers).

9 3 mils = 2.5 E-04 ft

Table 3-2. Mass Insulation Material Debris Characteristics[1]

Debris Name	Insulation Material Description	As-Fabricated Density (lb/ft^3)	Material Density (lbm/ft^3)	Characteristic Size[2]	
				µm	inch
PCI's Nukon Blankets	Removable and reusable blankets with woven glass fiber cloth covering fibrous glass insulating board (referred to by the NRC as a "LDFG")	2.4	159	7.0 fiber diameter	28E-05
Fiberglass – preformed pipe	Knaupf fibrous glass wool preformed into cylindrical shapes	4.0 +/- 10% or	159	7.5 fiber diameter	30E-05
Fiberglass – preformed pipe	Owens-Corning fibrous glass wool preformed into cylindrical shapes	3.5 to 5.5	159	8.25 fiber diameter	33E-03
Fiberglass – pipe and tank wrap	Fibrous glass wool wrap, using perpendicularly oriented fibers, adhered to an all-service jacketing (ASJ) facing (made by Knaupf, Owens-Corning, and others)	3.0 +/- 10%	159	6.75 fiber diameter	27E-05
Transco's Thermal Wrap Blankets	Removable and reusable blankets with woven glass fiber cloth covering fibrous glass insulation)	2.4[Ref. 17]	159	5.5 fiber diameter	22E-05
Knaupf	Knaupf ET Panel (LDFG similar to Nukon)	2.4	159	5.5 fiber diameter	22E-05
Temp-Mat and Insulbatte	Glass fibers needled into a felt mat; these are trade names of insulation products made by JPS Corp.	11.8[Ref. 9]	162[Ref. 9]	9.0 fiber diameter	36E-05 max. average[Ref. 13]
Cellular Glass	Foamglas is the trade name for this cellular glass product made by Pittsburgh Corning Corporation	6.1 to 9.8 (mean value of 7.5)	156	NA	0.05 to 0.08 pore size, grain size unknown
Kaowool	Needled insulation mat made from ceramic fibers; Kaowool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12[Ref. 10]	160 to 161	2.7 to 3.0 fiber diameter	10.8 to 12.0 E-05
Cerawool	Needled insulation mat made from ceramic fibers; Cerawool is a trade name for a family of ceramic fiber products made by Thermal Ceramics, Inc.	3 to 12[Ref. 10]	156 to 158	3.2 to 3.5 fiber diameter	12.8 to 14.0E-05
Mineral Wool	Generic name for families of products made by Rock Wool Mfg., Roxul, Fibrex, IIG, and others	4, 6, 8, 10 are standard	90	5 to 7 fiber diameter	20 to 28 E-05

Table 3-2. Mass Insulation Material Debris Characteristics[(1)] (Cont'd)

Debris Name	Insulation Material Description	As-Fabricated Density (lb/ft3)	Material Density (lbm/ft3)	Characteristic Size[(2)]	
				µm	inch
K®	Trade name of microporous insulation products made by Thermal Ceramics, Inc. from fumed silica, glass fibers, and quartz fibers	8 to 16	NA	< 0.1	< 4E-06
Calcium Silicate	Manufactured by IIG in three locations (2 use diatomaceous earth, 1 uses expanded perlite)	14.5	144[(Ref. 11)]	5 µm mean particle size (2 to 100 µm range)[(Ref. 16)]	20E-05
Microtherm	Microporous Insulation	5 to 12 [(Ref. 13)]	NA	<0.2	<4.0E-06
Asbestos	Structural fiber used in Cal-Sil type ins.	7 to 10[(Ref. 12)]	153	1 to 8	4 to 32E-05

1. For materials not listed, the manufacturer should be contacted for the information.
2. The sizes listed are to be used in the NUREG/CR-6224 head loss correlation as initial values in the absence of applicable experimental data.

The NRC refers to the insulation fillers in Nukon, Thermal Wrap, and Knaupf-ET as "low density fiberglass" (LDFG). The LDFG materials are soft, loose and contain minimal binders. There are extensive test data for LDFG. There are also some glass fiber felt mat insulation materials and these include Temp-Mat® and Insulbatte® insulations, both made by JPS Corp., as well as some by other trade names such as AlphaMat® by Alpha Inc. Again, these are relatively soft and loose. Other fibrous materials include ceramic felt mat insulation, two of which are Kaowool® and Cerawool®, both by Thermal Ceramics, Inc.

Finally, there are mineral wool insulation products with a number of different trade names, forms, and densities. Major North American manufacturers include Rock Wool Manufacturing, Roxul, Fibrex, IIG, and Thermafiber. These materials have higher densities and are generally stiffer, having more binder and particulate. While mineral wool has been widely used in Europe, it has limited use in North American nuclear containments. Mineral wool was the original drywell piping insulation at the Barseback Plant that was blown off by a lifted steam relief valve and which subsequently blocked ECCS strainers. In general, mineral wool is available in densities that are at least twice those of comparable fibrous glass wool insulations, up to ~10 pcf.

Asbestos insulation may be encountered at some plants. It is typically used as a structural fiber in calcium silicate insulation and sold under the trade name Unibestos.

Granular insulation materials include calcium silicate and microporous insulation. All the calcium silicate insulation in North America has been manufactured without the use of asbestos since about 1972. Produced by various manufacturers over the years, today all calcium silicate is manufactured by IIG, a joint venture between Calsilite Corp. and Johns-Manville Corp., at three factories. The only microporous insulation manufactured in North America is MinK, manufactured by Thermal Ceramics, Inc. today but by Johns-Manville for many years. Microtherm, manufactured in the UK, is also available in North America.

The only cellular insulation in Table 3-2 is cellular glass. Most of what has been installed in U.S. nuclear plants has been manufactured by Pittsburgh Corning Corporation and is known by its trade name, Foamglas®. This is an inorganic, rigid, and brittle cellular insulation typically used in containments on chilled water lines. However, for reference, there are numerous other types of cellular insulation available that are organic compounds. These include melamine, polystyrene, polyisocyanurate, phenolic, polyimide, polyolefin, flexible elastomeric, and polyurethane foams. There are numerous trade names by which these are known. The best known is Dow Chemical's Styrofoam, which is polystyrene foam insulation.

Failed Coatings

To properly characterize coating debris for the head loss evaluation, the type, mass, application thickness, particle sizes, and surface area or volume are necessary inputs, and these should be specified to the extent practicable in the debris generation and debris transport calculations. The quantity of a failed coating is adequately specified by the mass of the coating and its density. Alternatively, the surface area of the failed coating, along with its thickness and the density, can be used to determine the mass.

Unless replaced by plant-specific information of higher value, Table 3-3 lists the bulk density and the characteristic size and shape for various types of coating debris, and these can be used for the evaluation. The actual size distributions of these materials in a post-DBA environment are not known. Thus, the table lists particle sizes that are conservative (i.e., small) for head loss evaluations. Plant-specific data, if available, can supersede these data.

The following types of coatings are commonly found within PWR containments: inorganic zinc (IOZ), epoxy, epoxy-phenolic and alkyd. The densities for the epoxy, epoxy-phenolic, and alkyd coatings listed in Table 3-3 are based on specific gravities presented in the "Performance of Containment Coatings During a Loss of Coolant Accident." (Reference 18). The density for IOZ is 437 lbm/ft^3 as reported by Carboline for the zinc dust used in the formulation of CarboZinc-11.

This guidance assumes complete destruction of coatings within the coating ZOI. In the absence of specific experimental data about the debris particle size distribution for IOZ, alkyds, epoxy, and epoxy-phenolic coating debris generated by high-pressure water or steam jets in the ZOI, a diameter of 10 µm is assumed as the characteristic size of coating debris generated within the ZOI. The 10-µm characteristic diameter is the nominal diameter of unbound zinc particles and also the alkyd pigment particles of failed coatings. Coatings outside the ZOI that have not been demonstrated to be DBA-qualified or "acceptable," or whose qualification is "indeterminate," are assumed to fail as chips. A typical lower bound for epoxy and epoxy-phenolic coating chip thickness is 1 mil (25.4 µm). A 10-micron (10 µm) diameter is assumed as the characteristic size of debris from IOZ and alkyd coatings outside the ZOI that have not been demonstrated to be DBA-qualified or "acceptable," or whose qualification is "indeterminate."

Table 3-3. Coating Debris Characteristics

Generic Coating Material	Material Density (lb/ft^3)	Characteristic Size (µm)	Characteristic Size (ft)
Inorganic Zinc (IOZ)	457	10(1)	3.28E-05(1)
Epoxy and Epoxy Phenolic Coating Chips (outside ZOI)	94	25(2)	8.20E-05(2)
Epoxy and Epoxy Phenolic Coating Particles (in ZOI)	94	10(1)	3.28E-05(1)
Alkyd Coating	98	10(1)	3.28E-05(1)
Aluminum	90	10(2)	3.28E-05(2)

1. Spherical particle diameter
2. Flat plate thickness

3.5 LATENT DEBRIS

3.5.1 Discussion

The potential for latent debris in containment during plant operation that may impact head loss across the emergency core cooling sump screens should be considered. Therefore, it is necessary to determine the types, quantities, and locations of latent debris sources.

Due to the variations in containment design and size from unit to unit, many miscellaneous sources should be evaluated on a plant-specific basis. It is not appropriate for the licensees to say that their foreign materials exclusion (FME) programs can entirely eliminate sources of miscellaneous debris unless plant-specific walkdowns verify this. Plant-specific walkdown results can be used to determine a conservative amount of dust and dirt to be included in the debris source term. The walkdown will not be able to directly measure this type of debris. However, it is possible to quantify the amount of debris with additional steps.

It is recommended that the following activities be performed to quantify the amount of latent debris inside containment:

- Calculate the horizontal and vertical surface areas inside containment. This calculation will determine the total area with the potential for accumulation of debris.

- Evaluate the resident debris buildup. It is necessary to determine the amount of debris present on surfaces inside containment.

- Define the debris characteristics. This information will be used in subsequent steps of the sump performance evaluation.

- Calculate the total quantity and composition of debris. This information will also be used in subsequent steps of the sump performance evaluation, such as evaluation of the transport of latent debris to the sump screen and the resulting head loss.

Detailed guidance for accomplishing the recommended activities for quantification of the amount of latent debris is provided below.

3.5.2 Baseline Approach

Latent debris is a contributor to head loss across the sump screen and should be evaluated accordingly. Information is provided in the guidance below to evaluate the quantity of latent debris with sufficient rigor to eliminate excessive conservatism. Note, however, that in many cases, the contribution to head loss by latent debris will be small in comparison to that caused by debris from other sources such as insulation materials. In these cases, latent debris will not determine the course of action for mitigating ECCS sump strainer issues.

The impact on the results of the sump performance evaluation as a whole should be considered before performing an extremely rigorous analysis of latent debris loading. While it is possible to evaluate the effects of latent debris to a high degree of detail, use of conservative strategies is recommended. Furthermore, the use of conservative strategies in the evaluation of latent debris effects can provide for more head loss analysis margin and can improve operational flexibility if sump modifications are made.

3.5.2.1 Estimate Horizontal and Vertical Surface Area Inside Containment

Estimates are made of the horizontal and vertical surface areas. Vertical surfaces such as walls and sides of equipment are considered although a significant amount of debris does not typically collect on vertical surfaces in the absence of factors that promote adhesion of solids to the surface.

The following is a sample of the surfaces that are included in the surface area estimate:

- Floor area
- Walls
- Cable trays
- Major ductwork
- Control rod drive mechanism coolers
- Tops of reactor coolant pumps
- Equipment (such as valve operators, air handlers, etc.)

Other surfaces should be included as appropriate for plant-specific applications (junction boxes, etc.).

Use the following guidance in the calculations:

1. Flat surfaces are considered to be floors, cable trays, AOV diaphragms, and other flat or nearly flat surfaces. The bases for this are:

    - Unless the surface is highly convoluted (e.g., a heat exchanger or similar device), assuming a flat surface will not have a significant effect on the surface area calculation. Furthermore, the area projected onto the horizontal plane by the surface would be the key determining factor for the settling and accumulation of debris. For example, while a series of heat exchanger fins may have a large surface area, a significant percentage of that area could be vertical which would preclude accumulation of debris on much of the surface area.

    - The surface area calculations are greatly simplified if the intricacies of surfaces are not explicitly accounted for.

2. Half of the surface area of round surfaces such as conduits and ladder rungs is used. The basis for this assumption is that the lower half of the surface area is either inverted or tangent to the vertical plane, so accumulation of debris in this area does not occur. In reality, it is likely that the percentage of surface area susceptible to debris accumulation is less than half, because it is unlikely that debris would remain on the regions of the surface that are nearly vertical.

3. Ten percent of the vertical surfaces inside containment is used. The basis for this assumption is that accumulation of debris on vertical surfaces will typically not occur, but is considered for conservatism. Although walls are considered, the containment dome itself is not considered. Debris accumulation on this surface is precluded because it is inverted or tangent to the vertical plane.

4. Perform thorough calculations to determine the surface area to be considered for each area of containment. The information needed to perform the calculations can be obtained through plant drawings (plans) and photographic evidence obtained during containment walkdowns.

5. If exact dimensions are unavailable, use estimated dimensions. Acceptable sources of estimated dimensions are plant drawings (plans) that do not include explicit dimensions for the component in question (i.e., a representation of the component is shown but not detailed) and photographic evidence. Conservatively large values shall be used when dimensions are estimated and bases for the values used shall be provided.

3.5.2.2 Evaluate Resident Debris Buildup

Although recent sampling of surfaces inside containment at a number of plants indicated that it is likely that the maximum mass of latent debris inside containment is less than 200 pounds, it is recommended that a survey of the containment be performed, with the objective of determining the quantity of latent debris.

Surveying the containment for latent debris will ensure that higher-than-average debris loads are accounted for and will allow plants to take advantage of smaller latent debris loading if lower quantities are present.

Note that it will be necessary to perform periodic surveys (as part of outage efforts) to validate that there has been no significant change in the latent debris load inside containment. This evaluation of the presence of foreign material is described in NEI-02-01 (Reference 2). The necessary rigor of these surveys is dependent on the effectiveness of the licensee's FME and housekeeping programs with respect to containment cleanliness. If the licensee has rigorous programs in place to control the cleanliness of containment and documents the condition of containment following an outage, it is adequate to perform inspections and limited sampling of surfaces. If the cleanliness of containment is not controlled through rigorous programs, or if the programs in place do not address all areas of containment, it is necessary to perform more comprehensive surveys.

3.5.2.2.1 Evaluate the Resident Debris Buildup on Surfaces

To quantify the amount of latent debris on horizontal surfaces in containment, determine the thickness of the debris layer on a surface and the surface area the layer covers. This information can be used with the macroscopic debris density (with respect to volume) to determine the mass of debris present.

Use the following steps to evaluate the resident debris buildup on horizontal surfaces:

1. Divide containment into areas based on the presence of robust barriers. This will allow differing (from section to section) latent debris concentrations and compositions to be adequately represented and will facilitate subsequent debris transport calculations. Examples of appropriate areas include:

    - Accumulator rooms
    - In-core instrumentation room
    - Loop subcompartments
    - Steam generator or pressurizer subcompartments

2. Determine representative surfaces for each section of containment. For each section, this involves defining survey areas of known dimensions. The number of sampling areas examined per section of containment must be determined on a plant-specific basis. Use the following guidance to select representative surfaces:

- If the worst surface in a given section can be readily identified, it is acceptable to use that surface to represent the entire section. For example, if little or no debris is present on the surfaces in a section except for one, that one surface can be used to represent the debris accumulation in the entire section.

- If multiple surfaces have debris accumulation with different compositions and thicknesses, it is necessary to sample each of the surfaces to adequately represent the latent debris load for that section.

- If the area has a uniform and homogeneous latent debris load, a convenient surface can be chosen as the representative surface.

3. Survey the representative surfaces in each section to measure the debris quantity. Take care to ensure that all health physics procedures are followed for any samples collected. Two strategies are recommended.

   - Collect the debris using equipment that will allow measurement of the quantity of debris at a later time. The volume of debris collected is then divided by the surface area to determine the thickness of the debris layer.

     The collection method should allow estimation of the debris layer thickness and not change the macroscopic density of the debris that is collected. An acceptable method for collection is the use of swipes to remove the debris from the area in question. Since there is the potential to damage samples during the collection process, take care to not destroy or otherwise change the physical properties of the debris.

   - Measure or estimate the thickness of the debris layer directly. Since it is unlikely that a measurement device (such as calipers) can determine the layer thickness directly, it is recommended that the layer thickness be determined by comparison to an object of known or measurable thickness. Since the debris layers are expected to be quite thin (mils or fractions of mils), comparison to objects like sheets of paper or very thin sheets of metal is recommended.

   While it is possible to determine the thickness of the debris layer to an acceptable degree of accuracy, it may be difficult to accomplish, even if the debris layer is of uniform thickness and homogeneous composition. Therefore, care should be taken in the measuring process to achieve the most accurate results possible.

4. Calculate the thickness of the debris layer, based on the quantity of debris collected and the surface area of the sampling area.

3.5.2.2.2 Evaluate the Quantity of Other Miscellaneous Debris

In addition to determining the amount of latent debris accumulation on surfaces, other miscellaneous debris sources are to be accounted for in the debris source term. The survey of containment for these materials is to be performed consistent with the guidance in NEI 02-01 (Reference 2). Use the following guidance for each source to be considered:

- Equipment tags: Determine the number and location of equipment tags of each material type (paper, plastic, metal) within containment. Evaluate the transport of tags to the sump screen when performing the debris transport analysis (Section 3.6). Although paper tags may dissolve in the post-accident containment environment, it is conservative to assume that they remain intact and available for transport to the sump screen. This assumption shall be used unless there is information that indicates the tags will not remain intact.

- Tape: Determine the amount and location of each type of tape within containment. Evaluate the transport of tape to the sump screen when performing the debris transport analysis (Section 3.6). Although FME and housekeeping programs will remove most of the tape used during outage and construction activities, there may still be quantities present in containment. These pieces of tape could be in inaccessible areas or attached to components in plain view. Pieces of tape that have partially disintegrated from being in containment during plant operation should be considered in the latent debris source term. Additionally, tape affixed to surfaces such as ladder rungs to improve grip shall be assumed to fail and become transportable debris.

- Stickers or placards affixed by adhesives: Include items such as stickers and signs that are not mechanically attached to a structure or component in the latent debris source term. Evaluate the transport of these materials to the sump screen when performing the debris transport analysis (Section 3.6). It is likely that adhesives would fail in post-accident conditions. Assume that all stickers and placards affixed by adhesives fail and become transportable debris.

3.5.2.3 Define Debris Characteristics

Debris characteristics can be defined using two methods:

- Analyze debris samples to determine composition and physical properties.

- Assume composition and physical properties of the debris, using conservative values.

Because of the additional rigor and complexity as well as the additional time required to perform detailed analysis of the samples, it is recommended that conservative characteristics (with respect to head loss, as documented in Section 3.7) are assumed for the latent debris. The following debris characteristics should be used:

- Use an appropriate fiber/particulate mix for the plant being evaluated.

- Fiber density = 62.4 lbm/ft^3. The basis for this value is that it effectively makes the fiber neutrally buoyant, which results in maximum transport to the sump screen.

- Particle density = 100 lbm/ft^3. The basis for this value is that most particulate material can be categorized as "dirt." A representative material would likely be soil or sand, brought into containment during outage activities or construction. According to Reference 19, the densities of "Earth," dry and packed and "Sand" are both 95 lbm/ft^3. Therefore, 100 lbm/ft^3 is recommended.

- Particle diameter = 10 µm. Based on typical diameter of dust particles (Reference 20), a diameter of 10 µm is suggested. This diameter is conservatively small with respect to transport to the sump screen, since the diameter of "dirt" particles such as earth or sand is larger than that of dust. Furthermore, the diameter of 10 µm is consistent with the size of particles of failed coatings (Reference 21).

Note that ongoing research efforts by NRC and Los Alamos National Labs may provide additional information regarding the physical characteristics of latent debris.

If it is decided to analyze the debris samples to determine the composition and physical properties, the work should be performed by a laboratory experienced in material identification, analysis of the macroscopic and microscopic properties of material samples, and handling of radioactive materials. Note that there are challenges to effectively determining the debris characteristics by analysis:

- It is likely that thorough analysis of samples would be extremely expensive, possibly with little benefit.

- It is potentially impractical or impossible to separate the debris from the media or device used to capture it.

- It is possible that the macroscopic density of the debris as well as other characteristics will be changed during the sampling process or transportation to the analysis facility. These changes in characteristics would result because it is likely that the debris is not a homogenous solid; therefore it is possible for the debris to be compacted, damaged, or otherwise manipulated.

3.5.2.4 Determine Fraction of Surface Area Susceptible to Debris Accumulation

Not all areas are susceptible to accumulation of debris. For example, housekeeping activities at some plants may involve cleaning floors with special wipes, vacuum cleaners, or other methods. In these cases, the areas that are within the scope of the cleaning program could have essentially no debris accumulation, whereas inaccessible areas of the same surface could have an accumulation of debris. A single debris layer thickness would not accurately represent the entire surface.

It is appropriate to conservatively assume that the entire surface area is susceptible to debris accumulation. If it is unreasonable to use this assumption, in addition to determining the total horizontal surface area inside containment (per subsection 3.5.2.1) it is necessary to determine the fraction of the surface area of each component and surface that is susceptible to debris accumulation. To accomplish this, evaluate the fraction of the surface area susceptible to debris accumulation a component-by-component or surface-by-surface basis using the results from subsections 3.5.2.1 and 3.5.2.2 as input. Use the following guidance:

1. Assume that 100 percent of the surface area is susceptible to debris accumulation for inaccessible areas as well as accessible areas that are not thoroughly cleaned and documented as clean per plant procedures prior to restart (e.g., cable trays, junction boxes, and valve operators), and floors with gratings sitting on flat surfaces.

2. Evaluate the fractional area susceptible to debris accumulation for smooth floor areas and other surfaces cleaned per plant procedures prior to restart on a case-by-case basis. Considerations include the method of cleaning (e.g., pressure washing versus vacuuming) and accessibility of areas. Because of wide variations in containment design and effectiveness of housekeeping and FME programs, evaluations must be performed on a plant-specific basis.

   For all cases in which the area susceptible to debris accumulation is reduced, a conservatively large fractional area susceptible to accumulation must be determined, and bases must be provided for the fractions used. Use the following guidance:

   - Calculate the total surface area of the surface being considered.

   - Calculate the area of the surface that is clean. Use simplifying assumptions that will result in a conservatively small clean area.

   - Calculate the ratio of potentially dirty area to the total area.

3.5.2.5 Calculate Total Quantity and Composition of Debris

The final step in determining the quantity of latent debris located inside containment is to compute the total quantity of latent debris using the results from subsections 3.5.2.1 to 3.5.2.3 as input.

Use the following guidance when performing the final calculations:

1. The calculations should be performed on an area-by-area basis (consistent with subsections 3.5.2.1 to 3.5.2.3). Performing the calculations in this way will facilitate adequate representation of the debris densities and characteristics in the different areas inside containment.

2. Compute the total quantity of debris for each area by multiplying the total surface area susceptible to debris accumulation by the debris layer thickness for the area of containment being considered.

3. Include quantities of other types of latent debris such as tape, equipment tags, and stickers.

4. Categorize and catalog the results for input to the debris transport analysis.

3.5.3 Sample Calculation

The sample calculation considers the bottom level of containment. Equipment tags, tape, and stickers have been excluded from this example since minimal calculations are required for these items and guidance is included in Reference 2. The following surfaces are included in the calculation:

- Floor areas
- Cable trays
- Sump drain pumps

For an actual calculation, more detail and rigor are required to document all the surface area on a given level of containment. Since this is a sample calculation, only representative examples were used.

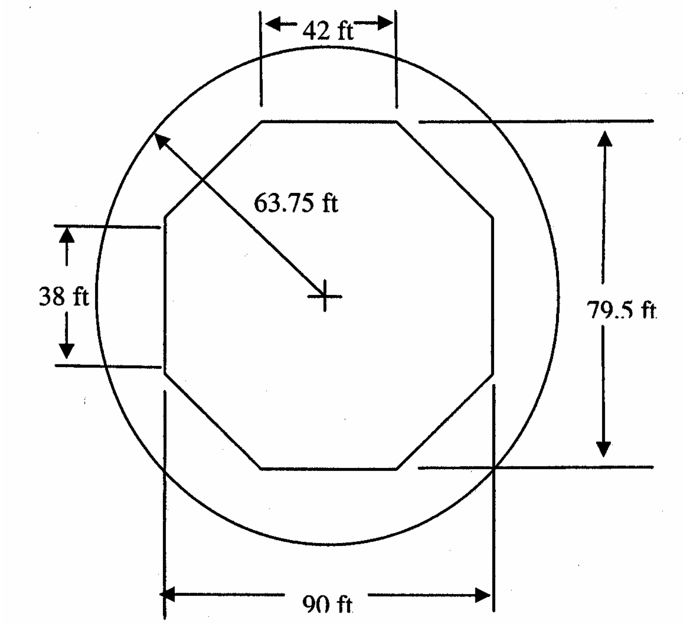
Subsection 3.5.3.1 documents the calculation of the horizontal areas for complex rooms and cable trays. Subsection 3.5.3.2 documents the calculation of the amount of debris present in the area being considered.

3.5.3.1 Calculate Horizontal Surface Area

The examples below show the calculation of a number of complex floor areas. Rooms of simpler geometry are calculated with less effort and therefore, examples of those calculations have not been shown.

1. Calculate area between containment shell and steam generator (SG) compartments.

   The floor area between the containment shell and SG compartments looks roughly like the region between the octagon and circle in the figure below:



Therefore, the area of the octagon is calculated as:

$$A = (90\ \text{ft})\ (75\ \text{ft}) - (4)\ (0.5)\ [(0.5)\ (79.5-38)]*[(0.5)\ (90-42)]$$
$$A = 5754\ \text{ft}^2$$

Subtract area of octagonal region from round region:

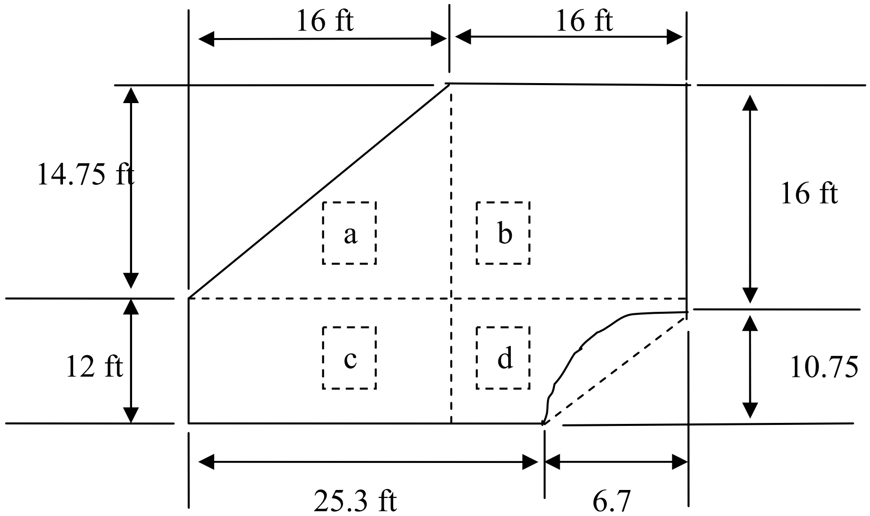
$$A = \pi\ (63.75\ \text{ft})\ 2 - 5754\ \text{ft}^2$$
$$A = 7014\ \text{ft}^2$$

Subtract area of the reactor coolant drain tank (RCDT) room and excess letdown heat exchanger room (these areas protrude from the rough octagonal shape):

$$A = 7014\ \text{ft}^2 - 56\ \text{ft}^2 - 94.6\ \text{ft}^2$$
$$A = 6914\ \text{ft}^2$$

2. Calculate area inside SG compartments.

Each SG compartment has a shape and dimensions roughly like the shape with the solid border below. To simplify the calculations, the room was divided into four regions and the round wall was assumed to be straight:



$A = a + b + c + d$

$a = 0.5(16\ ft)\ (14.75\ ft) = 118\ ft^2$

$b = (16\ ft)\ (14.75\ ft) = 236\ ft^2$

$c = (12\ ft)\ (16\ ft) = 192\ ft^2$

$d = (16\ ft)\ (12\ ft) – (0.5)\ (10.75\ ft)\ (6.7\ ft) = 156\ ft^2$

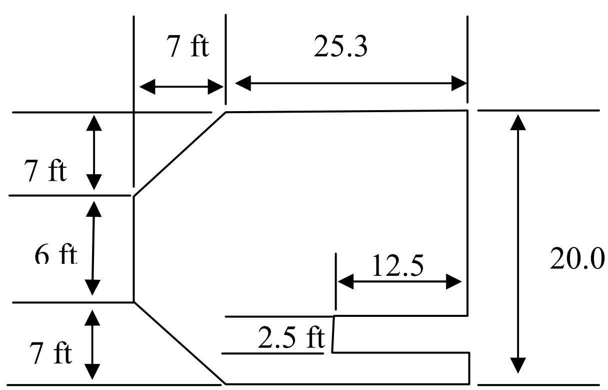
$A = 466\ ft^2$

$A_{total} = 4(A)$ (since there are four steam generators)

$= 1864\ ft^2$

3. Calculate area inside seal table room.

The geometry of the seal table room is as shown in the figure below. One simplifying assumption was with regard to the six-foot-long wall. It is actually curved and protrudes into the room, but was assumed to be straight. This assumption results in prediction of a conservatively large floor area.



$A = (32.3\ ft)\ (20\ ft) – (2)\ (0.5)\ (7.0\ ft)\ (7.0\ ft) – (2.5\ ft)\ (12.5\ ft)$

$A = 563.8\ ft^2$

4. Calculate area of cable trays and other components.

For this sample calculation, 300 linear feet of cable trays was assumed. It was also assumed that the trays were 1 foot wide, resulting in a total surface area of 300 ft^2. For all cable trays, the length and width should be documented and used to calculate the horizontal surface area.

The other example of component surface area in this sample calculation is the rectangular cover on the sump drain pumps, as shown in the spreadsheet below. It is noteworthy that the covers over the sump were documented as part of the floor area, since there is no floor area considered below them.

Other components were not examined in detail for this sample calculation. Components that should be examined include, but are not limited to:

- RCS piping and other piping
- Pressurizer relief tank
- Excess letdown heat exchanger (depending on location)
- Air handling units
- RCS draindown tank and associated heat exchanger
- Junction boxes

3.5.3.2 Calculate Quantity of Debris

This section documents sample calculations of the quantity of debris in the area considered. The calculations are relatively straightforward. To calculate the mass of debris in a given area:

Volume = (Debris layer thickness) * (Surface area)
Mass = (Volume) * (Density)

Example results are presented in Table 3-4. It is noteworthy that the results are for demonstration only and are based on hypothetical debris survey results.

3.6 DEBRIS TRANSPORT

3.6.1 Definition

Debris transport is the estimation of the fraction of debris that is transported from debris sources (break location) to the sump screen. The four major debris transport modes considered in the NEI Guidance are:

- Blowdown transport – the transport of debris by the break jet.
- Washdown spray transport – the vertical transport by the containment sprays/break flow.

Table 3-4. Sample Calculation of Debris Quantity

Description	Length ft	Width ft	Surface Area ft^2	Layer Thickness in	Percent Clean %	Debris Volume ft^3	Fiber by Volume %	Fiber Volume ft^3	Fiber Density lb/ft^3	Fiber Mass lb	Particulates Volume ft^3	Particulates Density lb/ft^3	Particulates Mass lb
Floor Areas													
1 Area between SG rooms and cont. shell			6914.0	1.00E-03	25.0	0.43	50.0	0.22	62.40	13.48	0.22	100.00	21.61
2 SG rooms (4 rooms)			1864.0	1.00E-03	25.0	0.12	50.0	0.06	62.40	3.63	0.06	100.00	5.83
3 RCDT room	24.00	8.00	192.0	1.00E-03	0.0	0.02	50.0	0.01	62.40	0.50	0.01	100.00	0.80
4 RCDT HX room	20.00	6.75	135.0	1.00E-03	0.0	0.01	50.0	0.01	62.40	0.35	0.01	100.00	0.56
5 RCDT HX room anteroom	13.30	11.25	149.6	1.00E-03	0.0	0.01	50.0	0.01	62.40	0.39	0.01	100.00	0.62
6 Excess letdown HX rm	22.25	4.25	94.6	1.00E-03	0.0	0.01	50.0	0.00	62.40	0.25	0.00	100.00	0.39
7 Seal table room			563.8	1.00E-03	0.0	0.05	50.0	0.02	62.40	1.47	0.02	100.00	2.35
Equipment													
1 Sump drain pump cover	6.00	4.00	24.0	1.00E-03	0.0	0.00	50.0	0.00	62.40	0.06	0.00	100.00	0.10
2 Cable trays	300.00	1.00	300.0	1.00E-03	0.0	0.03	50.0	0.01	62.40	0.78	0.01	100.00	1.25
Totals						0.67		0.34		20.91	0.34		33.51

Notes:
Sump top plate surface area included in Floor Area #1
Calculations for floor areas #1, 2, 7 documented separately
Debris layer thicknesses are hypothetical, not based on actual survey data.

- Pool fill-up transport – the horizontal transport of the debris by break and containment spray flows to active and inactive areas of basement pool.

- Recirculation transport – the horizontal transport of the debris in the active portions of the basement pool by the recirculation flow through the ECCS.

3.6.2 Discussion

For the NEI Guidance, the methodology used to determine the amount of debris transported is based on the methodology reported in Section 4.2 of NUREG/CR-6762, Vol. 4 (Reference 25). Figure 3-2 depicts the generic transport logic tree for use in the NEI Guidance.

Transport fractions for each branch are provided for debris from the ZOI as well as debris outside the ZOI. These transport fractions are provided for three general types of containments:

- Highly compartmentalized containments
- Mostly uncompartmentalized containments
- Ice condenser containments

Highly compartmentalized containments are those that have distinct robust structures and compartments totally surrounding the major components of the RCS, e.g., steam generator and pressurizer. Typical examples of these containments are Westinghouse three-loop plants and earlier Combustion Engineering (CE) plants with dry ambient atmosphere containments. Mostly uncompartmentalized containments are those that have partial robust structures surrounding the steam generators. Typical examples are the Babcock and Wilcox (B&W) dry ambient atmosphere plants. All of the seven ice condenser plants are four-loop Westinghouse plants with no compartmentalization in the lower containment. For breaks that are not inside a defined compartment, the transport fractions of the mostly uncompartmentalized containments should be used.

3.6.3 Debris Transport

Guidance is provided to calculate the debris transport values for each of the three major types of containments, for the major categories of debris: fibrous insulation in the break ZOI, RMI insulation in the break ZOI, other material in the ZOI, and debris outside the ZOI. The type of material found in each classification is provided in the debris characteristic section and the latent debris section.

The debris characteristic terminologies employed herein are those from the debris characteristics section. Small fines are defined as any material that could transport through gratings, trash racks, or radiological protection fences by blowdown, containment sprays, or post-LOCA pool flows. This guideline assumes the largest openings of the gratings, trash racks, or radiological protection fences to be less than 4 inches by 4 inches. The remaining material that cannot pass through gratings, trash racks, and radiological protection fences is classified as large pieces. For fibrous insulation material, the large pieces are assumed to be jacketed/canvassed, hence not subjected to further erosion.

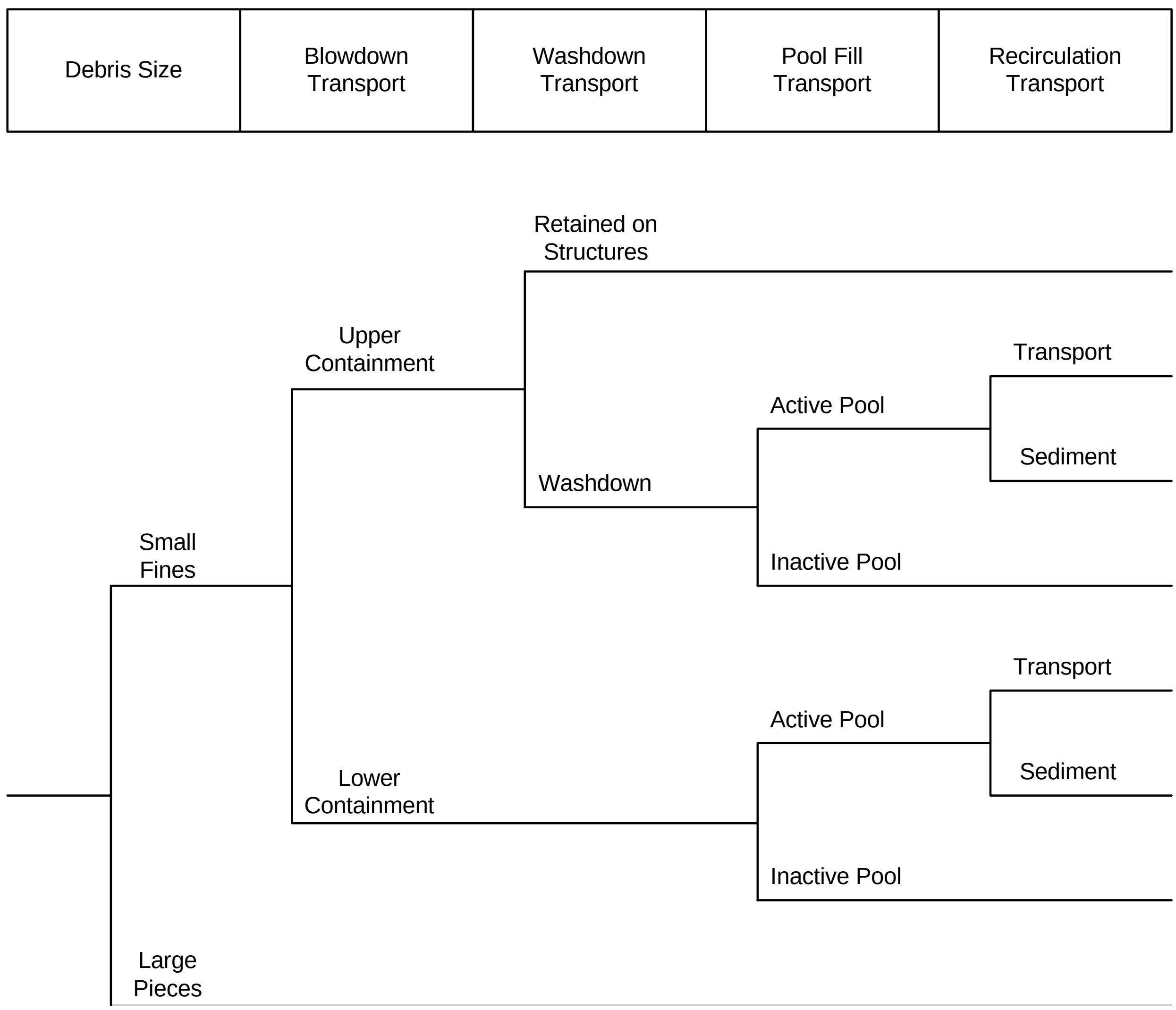


Figure 3-2. Unquantified NEI Guidance Logic Tree

The Baseline Evaluation guidance considers two transport modes for the containment bottom floor: pool fill transport and recirculation transport. All plants have a calculation determining the water level in containment following a DBA. This calculation provides estimates of the volume of each compartment that are considered to be flooded by the DBA. Using this calculation and a layout of the containment elevation, an analyst can determine which of the volumes are below the containment bottom floor. The analyst then needs to review all the lower compartments to ensure that those volumes do not have drains from the upper part of the containment (e.g., refueling pool) that may cause them to participate in the active volumes. This guideline considers that all volumes at the containment bottom floor elevation will participate in the recirculation flow path from the containment sprays and break flow to the sump.

During the filling of the containment bottom floor pool, as depicted in Figure 1-4 and 1-5 of NUREG/CR-6808 (Reference 6), the switchover to recirculation has not occurred, hence there is no preferential direction for water to flow to the sump.

In the pool fill transport, this NEI guidance considers that all debris in the containment bottom floor is uniformly distributed throughout the entire volume of water in containment. This guidance then considers that the debris transported to the inactive sumps is strictly based on the ratio of the volume of the inactive sumps to the total water volume in containment at the start of recirculation. This assumption is clearly conservative, since it ignores the preferential sweeping of the debris on the containment bottom floor to the inactive sumps by the thin sheets of high-velocity water. To add to the conservatism, this guidance then considers that all debris classified as “small fines” or “small RMI pieces” is transported to the sump during recirculation. Plants can deviate from the Baseline Evaluation guidelines to account for plant-specific features. Such deviations from the Baseline Evaluation guidance are considered refinements to the baseline methodology. Additionally, plants may consider implementing refinements identified in Sections 4 and 5 of this guide.

3.6.3.1 Highly Compartmentalized Containment

This guidance assumes that the pipe break in a highly compartmentalized containment occurs at the bottom of the compartment. For breaks that are not located in the bottom of the compartment or on upper portion of a compartment, e.g., a main steam line break, the mostly uncompartmentalized containment values should be used.

Fibrous Insulation in the ZOI

The following guidance is provided for all types of fibrous debris in the ZOI.

<u>Blowdown Transport</u>

Debris transport during blowdown is assumed to cause the small fines debris from the compartment where the break is postulated to occur to be distributed to all horizontal surfaces outside the compartments and the dome. Most of the break locations in a compartment are located in the bottom of the compartment. For conservatism, it is assumed that only 25 percent of the small fines debris is ejected upward, the rest going to the containment bottom floor. This fraction is derived as a conservative estimate of the free volume in a compartment above the lower portion of the compartment not occupied by components such as steam generators. The large debris pieces from the ZOI are assumed to fall to the compartment floor and not be transported.

Washdown Transport

Debris transport by the containment spray is assumed to cause all the small fines to be transported to the containment bottom floor and be evenly distributed on the floor. No transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the containment bottom floor pool during fill-up will transport all the small fines. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, i.e., the cavity under the reactor vessel. The transport factor to the inactive pools is determined by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small fines in the active volumes of the pool to the sump. No transport of the large pieces is assumed to occur during recirculation.

RMI Insulation in the ZOI

The following guidance is provided for all types of RMI debris in the ZOI.

Blowdown Transport

Debris transport during blowdown is assumed to cause the small RMI debris pieces from the compartment where the break is postulated to occur to be distributed to all horizontal surfaces outside the compartment. For conservatism, it is assumed that only 25 percent of the small RMI debris is ejected upward, the rest going to the containment floor. This fraction is derived as a conservative estimate of the free volume in a compartment above the lower portion of the compartment not occupied by components such as steam generators. The large RMI debris pieces from the ZOI are assumed to fall to the compartment floor and not be transported.

Washdown Transport

Debris transport by the containment spray is assumed to cause none of the small RMI debris that are not on the containment bottom floor and are in containment spray pathway to be transported to the containment bottom floor. The flow velocities and the very shallow pool depths are not conducive to transport of small RMI debris. No transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the containment bottom floor pool during fill-up will transport all the small RMI debris. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, i.e., the cavity under the reactor vessel. The transport factor to the inactive pools is determined by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No transport of the large RMI pieces is assumed to occur during recirculation.

Other Material in the ZOI

All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to transport similarly to the small fines of fibrous material.

Debris from Materials Outside the ZOI

All debris from materials outside the ZOI is considered to be in the active volumes of the pool at the start of recirculation and 100 percent transported by the active volumes of the pool to the sump. Latent debris is also considered to be to be in the active volumes of the pool at the start of recirculation and 100 percent transported by the active volumes of the pool to the sump. This is conservative since debris from outside the ZOI is not considered to be transported to the inactive sump.

3.6.3.2 Mostly Uncompartmentalized Containment

The following guidance is provided for all types of fibrous debris in the ZOI.

Fibrous Insulation in the ZOI

Blowdown Transport

Debris transport during blowdown is assumed to cause the small fines debris from the compartment where the break is postulated to occur to be distributed to evenly to all horizontal surfaces outside the compartments and the dome. The large debris pieces from the ZOI are assumed to fall to the containment bottom floor and not be transported.

Washdown Transport

Debris transport by the containment spray is assumed to cause all the small fines to be transported to the containment bottom floor and be evenly distributed on the floor. No transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the containment bottom floor pool during fill-up will transport all the small fines. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, i.e., the cavity under the reactor vessel. The transport factor to the inactive pools is calculated by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small fines in the active volumes of the pool to the sump. No transport of the large pieces is assumed to occur during recirculation.

RMI Insulation in the ZOI

The following guidance is provided for all types of RMI debris in the ZOI.

Blowdown Transport

Debris transport during blowdown is assumed to cause the small RMI debris pieces from the compartment where the break is postulated to occur to be distributed to all horizontal surfaces outside the compartments. For conservatism, it is assumed that all the small RMI debris is deposited on the containment bottom floor. The large RMI debris pieces from the ZOI are assumed to fall to the containment bottom floor and not be transported.

Washdown Transport

There is no debris transport by the containment spray of the small RMI pieces since all small RMI debris is assumed to be transported by the blowdown to the containment bottom floor. Also, no transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the containment bottom floor pool during fill-up will transport all the small RMI debris. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The transport factor to the inactive pools is determined by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No transport of the large RMI pieces is assumed to occur during recirculation.

Other Material in the ZOI

All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to transport similarly to the small fines of fibrous material.

Debris from Materials Outside the ZOI

All debris from materials outside the ZOI is considered to be in the active volumes of the pool at the start of recirculation and be 100 percent transported by the active volumes of the pool to the sump. Latent debris is also considered to be to be in the active volumes of the pool at the start of recirculation and be 100 percent transported by the active volumes of the pool to the sump. This is conservative, since debris from outside the ZOI is not considered to be transported to the inactive sump.

3.6.3.3 Ice Condenser Containment

Fibrous Insulation in the ZOI

The following guidance is provided for all types of fibrous debris in the ZOI.

Blowdown Transport

Debris transport during blowdown is assumed to cause most of the small fines debris from the lower containment where the break is postulated to occur to be transported to the upper compartment and the dome through the ice condenser baskets. Ten percent of the small fines debris is retained in the upper compartment and the ice condensers, the rest returning back to the lower containment floor by the melting ice. Steam and water with entrained debris will pass through the ice condenser cavities. Some of the debris will be entrained in the baskets. At the end of blowdown, at least 50 percent of the ice will have melted. Ten percent is a conservative average value of the open area in the ice condenser. The large debris pieces from the ZOI are assumed to fall to the lower containment floor and not be transported.

Washdown Transport

All the small fines that were transported to the upper containment by the blowdown will be conservatively assumed to be transported by the containment sprays from the upper containment to the lower containment bottom floor and be evenly distributed on the lower containment bottom floor. No transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the lower containment bottom floor pool during fill-up will transport all the small fines. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The transport factor to the inactive pools is determined by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small fines in the active volumes of the pool to the sump. No transport of the large pieces is assumed to occur during recirculation.

RMI Insulation in the ZOI

The following guidance is provided for all types of RMI debris in the ZOI.

Blowdown Transport

Debris transport during blowdown is assumed to cause most of the small RMI debris from the lower containment where the break is postulated to occur to be transported to the upper compartment and the dome through the ice condenser baskets. For conservatism, it is assumed that only 10 percent of the small RMI debris is transported to the upper compartment, the rest returning back to the lower containment bottom floor by the melting ice. Steam and water with entrained debris will all pass through the ice condenser cavities. Some of the debris will be entrained in the baskets. At the end of blowdown, at least 50 percent of the ice will have melted. Ten percent is a conservative average value of the open area in the ice condenser. The large debris pieces from the ZOI are assumed to fall to the lower containment bottom floor and not be transported.

Washdown Transport

Debris transport by the containment spray is assumed to cause none of the small RMI debris that is on the upper containment bottom floor and in the containment spray pathway to be transported to the containment bottom floor. The flow velocities and the very shallow pool depths in the upper containment floor are not conducive to transport of small RMI debris. No transport of the large pieces is assumed to occur by containment spray.

Pool Fill Transport

Debris transport in the lower containment bottom floor pool during fill-up will transport all the small RMI debris. Some of the small fines will be transported to the inactive volumes of the pool that will not participate in the recirculation flow, e.g., the cavity under the reactor vessel. The transport factor to the inactive pools is calculated by calculating the ratio of the volumes of the inactive pool to the total pool volume. No transport of the large RMI pieces is assumed to occur during pool fill-up.

Recirculation Transport

Debris transport in the containment bottom floor pool during recirculation is assumed to transport 100 percent of the small RMI debris in the active volumes of the pool to the sump. No transport of the large RMI pieces is assumed to occur during recirculation.

Other Material in the ZOI

All other material in the ZOI, including coatings within the coatings ZOI, will be assumed to transport similarly to the small fines of fibrous material.

Debris from Materials Outside the ZOI

All debris from materials outside the ZOI is considered to be in the active volumes of the pool at the start of recirculation and be 100 percent transported by the active volumes of the pool to the sump. Latent debris is also considered to be in the active volumes of the pool at the start of recirculation and be 100 percent transported by the active volumes of the pool to the sump. This is conservative, since debris from outside the ZOI is not considered to be transported to the inactive sump.

3.6.4 Calculate Transport Factors

The calculation of the transport factors for each type of debris is done by using the unquantified logic tree as a guide. A logic tree should be developed for each of the debris types and using the previously discussed values for the appropriate containment type. The summation of the two "Transport" branches is the cumulative transport fraction for the debris type.

3.6.4.1 Sample Calculation

The baseline sample plant is classified as a highly compartmentalized containment. From the post-DBA water level calculations, we have that the inactive pools account for 30 percent of the total post-DBA water volume in containment.

From the debris classification section, there are two types of debris from the ZOI for the baseline sample plant: Nukon and RMI. Using the recommended transport fractions, we have the following.

Nukon

Figure 3-3 is a quantified logic tree for Nukon.

Adding the two paths that reach the sump, the total cumulative transport factor for Nukon fines reaching the sump is 0.11 + 0.32 = 0.43. As such, 43 percent of the volume of Nukon in the ZOI reaches the sump in the form of small fines. No large pieces of Nukon will be transported to the sump.

RMI

Figure 3-4 is a quantified logic tree for the RMI.

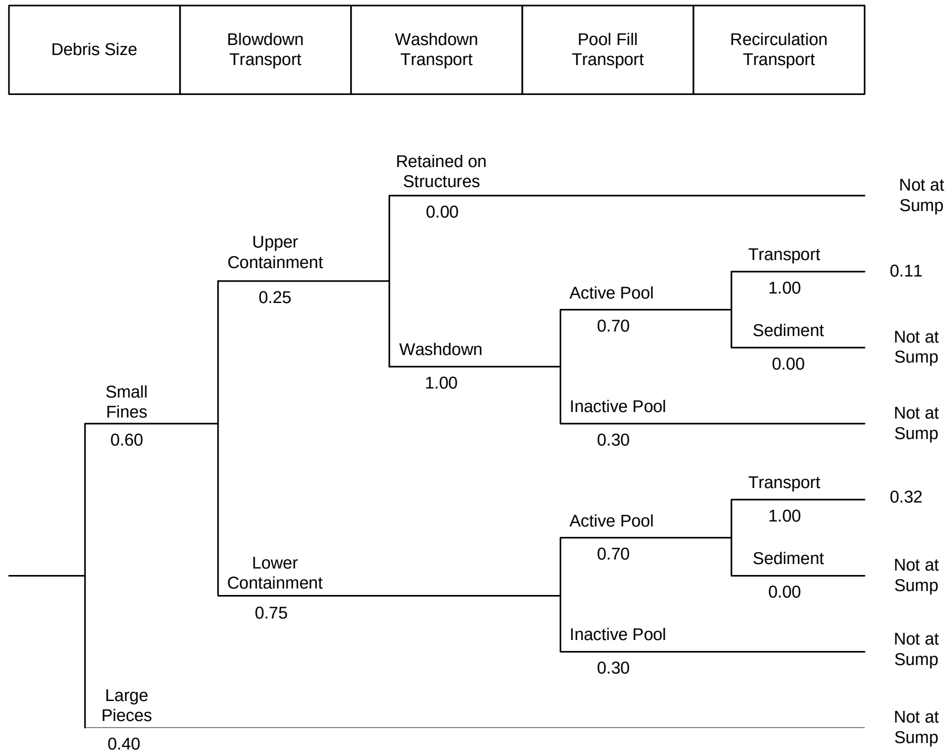


Figure 3-3. Nukon Transport Logic Tree (Sample Problem)

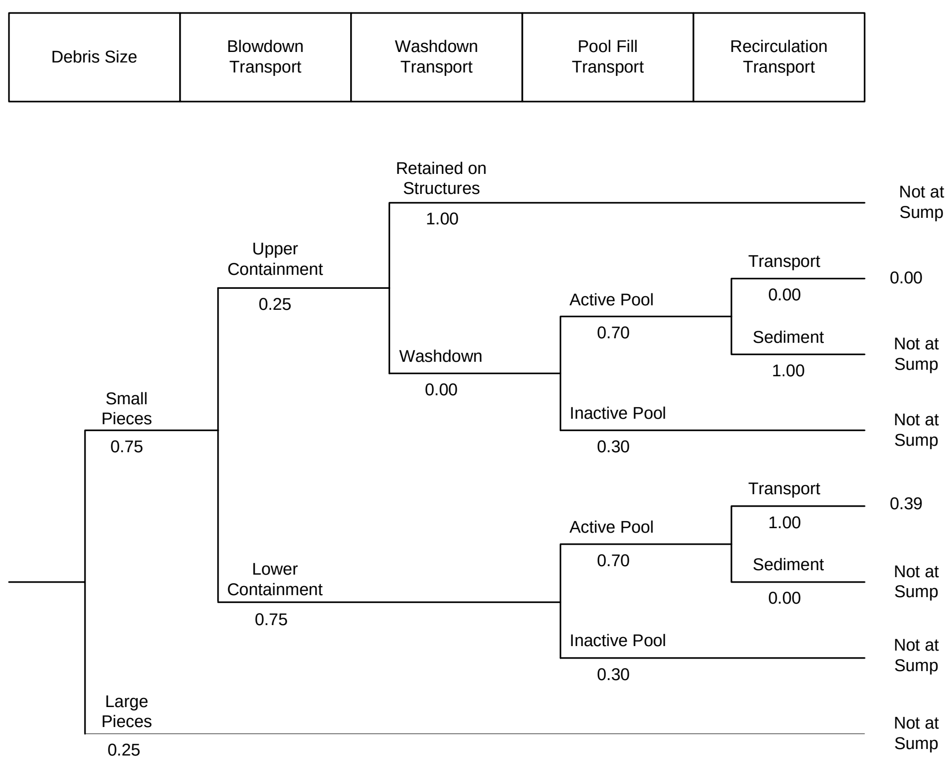


Figure 3-4. RMI Transport Logic Tree (Sample Problem)

From inspection of the logic tree, 0.39 is the transport factor for RMI. As such, 39 percent of the volume of RMI in the ZOI reaches the sump in the form of small pieces. No large RMI pieces will be transported to the sump.

Coating debris material from both from within the coatings ZOI and from outside the coatings ZOI will all be transported to the sump. All debris material outside the ZOI, including latent debris, will also be transported to the sump.

From the debris generation sample calculations, we have:

Total volume of Nukon blankets in ZOI: 300 ft^3
Total quantity of RMI material in ZOI: 15,000 ft^2

From the debris characterization section, we have:

Total Quantity of small fines coating:
0.007 ft^3 from the ZOI + 7.5 cu ft from outside the ZOI = 7.5 ft^3

From the latent debris section, we have:

Latent fiber:	20.91 lb @ 62.4 lb/ft^3 = 0.34 ft^3
Latent particulates:	33.51 lb @ 100 lb/ft^3 = 0.34 ft^3

Using the transport fractions derived above, the following quantities of debris are transported to the sump:

Fibers: small fines:	300 * 0.43 + 0.34	= 129.34 ft^3
RMI small pieces:	15,000 * 0.39	= 5,850 ft^2
Coating small fines (IOZ equivalent):		= 7.5 ft^3
Latent particulates:		= 0.34 ft^3

3.7 HEAD LOSS

3.7.1 Introduction and Scope

The methodology presented within this chapter details how to calculate the head loss from a debris bed that could be formed on the ECCS sump screen(s). The sump screen parameters and the thermal-hydraulic conditions required for this analysis will first be discussed. The types, total quantities, and characteristics of debris that are generated in the containment and transported to the sump screen are also primary design inputs for this methodology.

The methodology will provide the user with the head loss (feet of water) for the debris bed on the sump screen. The user then has to add the estimated clean sump screen head loss to obtain the total head loss across the sump screen. The ability to sustain this head loss is then assessed by comparison to the NPSH margin. Sample problems are provided to illustrate the methodology.

3.7.2 Inputs for Head Loss Evaluation

3.7.2.1 Sump Screen Design

The sump screen design is an important consideration in the evaluation of debris head loss. Plant drawings should provide details as to the screen construction, the orientation and the mesh size (or hole size and pitch for perforated plates). Typical PWR sump screen configurations are illustrated in Figure 3-5. Newer designs, such as those installed in the BWRs, typically have more surface area and different geometries.

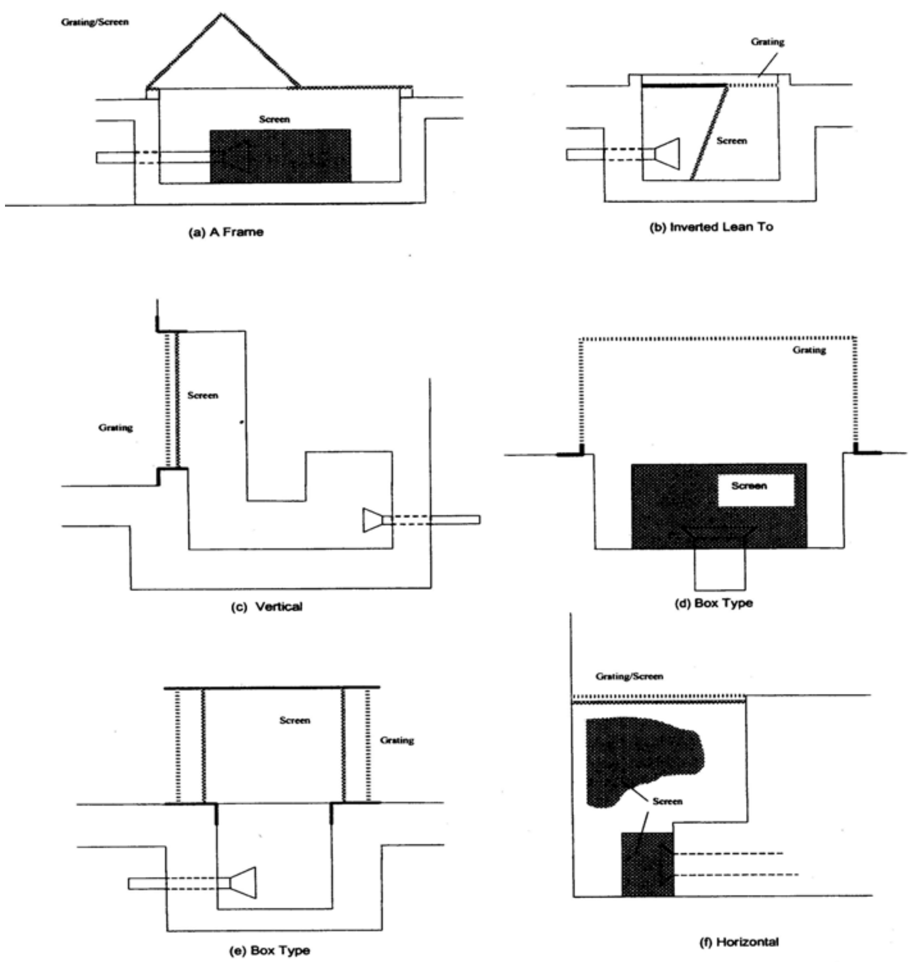


Figure 3-5. Typical PWR Sump Screen Configurations

Derived from plant drawings, the sump screen area (A) is the total area of the sump screen (without any correction for the solid area of the mesh or wire screen) over which debris accumulates. Curbs are ignored when determining the screen area. For flat screens, the sump screen is simply the total circumscribed area of the screen or perforated plate. Framing and/or significant structures that block flow through the screen should be subtracted from the total area to get a net screen area. For alternate geometries, particularly in the case of star or stacked-disc designs, the initial strainer surface area available for debris deposition is the total perforated plate surface area, decreasing to the circumscribed area as debris fills in the voids and gaps between the ridges and disks.

If the screen is completely submerged, the net screen area is used. If the screen is partially submerged, the wetted area should be determined based on the height of the containment floor water pool at the time the head loss is calculated.

The sump screen opening size (or hole size and pitch for perforated plate screens) is obtained from plant drawings. The opening size is usually the size needed to keep out debris of a size greater than the minimum size of openings in the ECCS (e.g., spray nozzles, valve throats, and pump cooling lines). The sump screen opening size is used in determining the clean strainer head loss. The debris-bed head loss calculation methodology adopted in this chapter is largely independent of the sump screen opening size.

The clean strainer head loss (CSHL) is the head loss of the sump screen assembly in a clean, unfouled condition. The CSHL is a required input for the overall head loss evaluation and is highly dependent on plant-specific sump screen construction details and thermal-hydraulic conditions. Calculating the head loss of the sump screen assembly in a clean condition involves calculating the head loss across the screen itself taking submergence of the screen into consideration. The CSHL will mainly depend on the screen mesh size (or hole size and pitch for perforated plates), the flow through the screen, and the water temperature using standard methods of fluid mechanics. This baseline methodology does not provide details on how to calculate clean strainer head loss as this information is available from other sources. Clean sump screen head loss information is typically available from the manufacturer of the raw screen material itself. Note that existing plant calculations often document CSHL. In some cases, the head losses due to the attendant support structures, mechanical configuration of the bracing, and other structures in the sump (such as vortex suppressors) cannot be neglected, and these losses should normally be included in the CSHL calculation.

3.7.2.2 Thermal-Hydraulic Conditions

3.7.2.2.1 Recirculation Pool Water Level

For conservatism, the minimum water level of the recirculation pool should be used to estimate the head loss across the debris bed accumulated on a screen. The minimum level will yield the smallest surface area (thus potentially greater head loss) for those screens that are not completely submerged in the pool as well as the lowest available NPSH to the ECCS pumps.

3.7.2.2.2 ECCS Flow Rate

For conservatism, the highest flow rate (Q) should be used in calculating the head loss across a screen. In this regard, the Baseline Methodology recommends that maximum pump flows, as identified in current NPSH calculations, be used for the ECCS flow rates. For multiple sump screens, the flow rate for the head loss calculation is the flow through each of the screens.

3.7.2.2.3 Temperature

The recirculation sump water temperature should be documented in the plant design basis calculations and is an important parameter in the head loss calculation.

The Baseline Evaluation Methodology recommends the following:

1. The temperature at which the head loss is evaluated should be consistent with the temperature used for the NPSH evaluation.

2. However, it is not clear which temperature is limiting overall; therefore, multiple times, temperatures, and flows during the accident may need to be evaluated. (For example, use of 250°F gives a head loss of 8.8 feet for the sample problem of this section, whereas using 120°F gives 33.9 feet).

3. As a conservative simplification, the maximum expected sump temperature may be used for the NPSH analysis, whereas the lowest expected temperature during ECCS operation may be taken for the head loss analysis.

3.7.2.2.4 Debris Types, Quantities, and Characteristics

Fibrous insulation debris, RMI debris, coatings debris, and miscellaneous debris such as concrete debris, dust, dirt, other latent debris, rust, etc. all have to be considered if they are present inside the containment. Therefore, the types, quantities (mass or volume), and characteristics of all potential debris materials need to be specified in the design input for a sump screen head loss evaluation. For fibrous materials, the insulation volume is the main parameter needed. For particulate materials, the mass and the density are the main parameters required. For RMI, the main parameter needed is the total foil area of the damaged RMI.

The composition and characteristics of the debris bed on the sump screen are important inputs into the head loss model. The debris types, quantities (i.e., mass or volume), and characteristics (e.g., shape and thickness) reaching the sump screen are needed to calculate the pressure drop across the debris bed. The debris types and potential quantities at the sump screen are determined by the debris generation and transport calculations.

3.7.2.3 Head Loss Methodology

The head loss model assumes that the screen is initially clean and that the floor pool contains a homogenous mixture and concentration of debris (i.e., fibrous, particulate, etc.). Upon switchover of suction from the refueling water storage tank (RWST) to the recirculation sump, debris begins to be transported to the sump and accumulates on the sump screen. Initially, some portion of the debris whose size is smaller than the screen mesh size (or hole-size of the perforated plate) passes through the sump screen. Fibers will quickly start to form a fiber mat in the cases where there is no RMI debris transported to the sump screen. (If RMI is present at the screen, refer to the mixed debris bed discussion in subsection 3.7.2.3.1.3). As the fiber mat forms, it will start trapping particulate debris reaching the sump screen. With sufficient fibers reaching the screen, a uniform fiber mat bed will be formed, at which time the head loss across the debris will start increasing. The head loss across the debris bed will continue to rise as more debris is deposited on the screen, reaching steady state when all of the available debris is deposited on the screen.

Most analysts are interested in the head loss across the sump screen when all debris reaching the sump screen accumulates on the screen. The head loss methodology herein provides the ability to compute the sump screen head loss given the total quantity and type of debris over a specified surface area at a given ECCS pump flow.

3.7.2.3.1 General Theoretical/Empirical Formulas

3.7.2.3.1.1 Fibrous Debris Beds with Particulate

For general use with fiber and particulate debris beds, the NUREG/CR-6224 correlation is recommended for determination of the head loss. The refinement guidance of Section 4 provides a discussion of factors associated with estimating debris head losses and presents several debris head loss correlations developed over the last few years.

The NUREG/CR-6224 head loss correlation is described and validated in detail in Appendix B of that report and is a semi-theoretical head loss model. The correlation is based on the theoretical and experimental research in head loss across a variety of porous and fibrous media carried out since the 1940s. The NUREG/CR-6224 head loss correlation has been thoroughly validated for fibrous debris and ferrous sludge found in BWRs for a variety of flow conditions, water temperatures, and in different experimental facilities. The types of fibrous insulation material tested include Nukon and Temp-Mat. The particulate matter debris tested includes iron oxide particles from 1 to 300 μm in characteristic size, plus inorganic zinc and paint chips. In these cases, with the appropriate selection of particle sizes as described in Tables 3-2 and 3-3 of this document, the NUREG/CR-6224 head loss correlation bounds the experimental results.

U.S.NRC Regulatory Guide 1.82, Revision 3 states that estimates of head loss caused by debris blockage should be developed from empirical data based on the sump screen design (e.g., surface area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and approach velocity. Therefore, there may be materials and combinations of materials for which the empirical head loss data do not exist. In these cases, the following options are available:

- Characterization of the material with scanning electron microscopy (SEM) analysis, and establishing a size distribution.

- Choosing an alternative material that conservatively represents the material in question, via similitude arguments.

- Head loss testing of the particular material to establish a correlation or else validate an existing correlation for that material.

- Utilize other data that may exist to establish head loss for the material in question. (The refinement guidance presented in Section 4 summarizes some of the industry test data. More data are possibly available, some of which are currently the property of individual utilities.)

The NUREG/CR-6224 head loss correlation, applicable for laminar, transient, and turbulent flow regimes through mixed debris beds (i.e., debris beds composed of fibrous and particulate matter) is given by:

$$\Delta H = \Lambda \, [3.5 \, S_v^2 \, \alpha_m^{1.5} \, (1 + 57 \, \alpha_m^3) \, \mu \, U + 0.66 \, S_v \, \alpha_m/(1-\alpha_m) \, \rho \, U^2] \, \Delta L_m \quad \text{(Equation 3.7.2-1)}$$

where:

ΔH is the head loss (feet of water)
S_v is the surface-to-volume ratio of the debris (ft^2/ft^3)
μ is the dynamic viscosity of water (lbm/ft/sec)
U is the fluid approach velocity (fps)
ρ is the density of water (lbm/ft^3)
α_m is the mixed debris bed solidity (one minus the porosity)
ΔL_m is the actual mixed debris bed thickness (inches)
Λ is a conversion factor –
$\Lambda = 1$ for SI units, and
$\Lambda = 4.1528 \times 10^{-5}$ (ft-water/inch)/($lbm/ft^2/sec^2$) for English units.

The fluid approach velocity, U, is given simply in terms of the volumetric flow rate and the effective screen surface area as:

$$U = \frac{Q}{A}$$

where:

Q is the total volumetric flow rate through the screen (ft^3/sec) and
A is the effective screen surface area (ft^2).

The screen surface area, A, is the submerged (wetted) effective surface area of the screen as described in subsection 3.7.2.1 above. As noted previously, the available surface area may change with time, particularly in the case of star or stacked-disc designs. For these particular alternate geometry screens, given sufficient debris reaching the screen, the effective surface area may eventually decrease to the circumscribed area. At the limit, the head loss for alternate geometry screens may be calculated using the circumscribed area and the debris load equal to the total debris load transported to the screen less the quantity of debris required to fill in the volumes and gaps of the alternate geometry screen.

The mixed debris bed solidity (α_m) is given by:

$$\alpha_m = \left(1 + \frac{\rho_f}{\rho_p}\eta\right)\alpha_o\, c \qquad \text{(Equation 3.7.2-2)}$$

where:

α_o = the solidity of the original fiber blanket (i.e., the "as fabricated" solidity)

η = mp/mf, the particulate-to-fiber mass ratio in the debris bed

mp = Σ mi is the total particulate mass (lbm)

ρ_f = the fiber density (lbm/ft^3)

ρ_p = the average particulate material density (lbm/ft^3) = $\Sigma\, \rho_i V_i / \Sigma\, V_i$

c = the head-loss-induced volumetric compression of the debris (inches/inch).

For debris deposition on a flat surface of a constant size, the compression (c) relates the actual debris bed thickness, ΔL_m, and the theoretical fibrous debris bed thickness, ΔL_o (inches), via the relation:

$$c = \frac{\Delta L_o}{\Delta L_m} \qquad \text{(Equation 3.7.2-3)}$$

Compression of the fibrous bed due to the pressure gradient across the bed is also accounted. The relation that accounts for this effect, which must be satisfied in parallel to the previous equation for the head loss, is given by (valid for ratios of $\Delta H/\Delta L_o > 0.5$ ft-water/inch-insulation):

$$c = 1.3 * K * (\Delta H/\Delta L_o)^{0.38} \qquad \text{(Equation 3.7.2-4)}$$

Here, "K" is a constant that depends on the insulation type. It is 1.0 for Nukon fiber. Test data or a similitude analysis are required to determine "K" for fibrous materials that are dissimilar to Nukon. It should be noted that this formulation for debris bed compression may overpredict compression significantly in the case of very thick debris layers, roughly 6 inches or more. Thus, in these cases, it is conservative.

For very large pressure gradients and for cases where very little fiber is present, the compression has to be limited so that a maximum solidity is not exceeded. In NUREG/CR-6224, this maximum solidity is defined to be:

$$\alpha_m = 65 \text{ lbm/ft}^3/\rho_p \qquad \text{(Equation 3.7.2-5)}$$

which is equivalent to having a granular debris layer with a bulk density of 65 lbm/ft^3. Note that 65 lbm/ft^3 is the macroscopic, or bulk density of a granular media such as sand or gravel and clay (Reference 6). Based on NUREG/CR-6224 (Reference 17), the above value is also appropriate for ferrous sludge. For a sludge particle density of ~324 lbm/ft^3, the maximum solidity is ~20 percent, and this value has been determined from test data to yield acceptable results with the NUREG/CR-6224 head loss correlation. In general, solidity is defined as:

$$\alpha_m = \rho_b/\rho_p \qquad \text{(Equation 3.7.2-5a)}$$

where ρ_b is the bulk, or macroscopic density, and ρ_p is the particle, or grain density. Since the solidity depends on the material properties, different materials may require testing to establish appropriate values. In practice, however, the limiting value of solidity specified above works well for many particulate mixtures.

Each constituent of debris has a surface-to-volume ratio associated with it based on the characteristic shape of that debris type. For typical debris types, we have:

Cylindrically shaped debris:	$S_v = 4/\text{diam}$
Spherically shaped debris:	$S_v = 6/\text{diam}$
Flakes (flat plates):	$S_v = 2/\text{thick}$

where "diam" is the diameter in feet of the fiber or spherical particle, and "thick" is the thickness in feet of the flake/chip. Other debris not listed above would have its surface-to-volume ratio calculated similarly based on one of the above characteristic shapes. Clearly, the above relations are simplified approximations. Generally, what is done is to select a characteristic size, for example, small spheres to represent irregularly shaped particulate debris, small cylinders to represent fiber, etc. Whatever modeling approach is used, a comparison to test data then has to be made to assess the validity of the approximation for that particular material, with the characteristic sizes adjusted as required for the head loss correlation to conservatively match the data. For debris not yet tested and for which similitude arguments cannot be made, SEM analysis and/or plant-specific testing may be required.

The following is a method for calculating the average surface to volume ratio for two different types of debris constituents (Reference 22).

$$S_v = \text{SQRT}\,[(S_{V1}^2 * v_1 + S_{V2}^2 * v_2)/(v_1 + v_2)] \qquad \text{(Equation 3.7.2-6)}$$

where v_1 and v_2 are the microscopic volumes of constituents "1" and "2," respectively.

Clearly, this result can be extended to more than two such fiber species as follows:

$$S_v = \text{SQRT}\,[\Sigma(S_{Vn}^2 * v_n)/\Sigma(v_n)] \qquad \text{(Equation 3.7.2-7)}$$

where the subscript "n" refers to the nth constituent.

Averaging in the above manner will yield a higher pressure drop as more than one type of debris is added to the mixture.

Tables 3-2 and 3-3 list recommended values of fiber and particle sizes based on the data currently available, from which values of S_V may be derived. Where values are not given or where uncertainty otherwise exists, it is best to err on the low side for conservative values of S_V. In some cases, further measurements to establish debris sizes, SEM analysis, and comparisons to head loss correlations and test data may be required to establish appropriate values.

To obtain an aggregate density for both particulate and fibrous debris, a simple volume averaging procedure is appropriate, as indicated in association with Equation 3.7.2-2, since, for a well-mixed debris bed, the individual species can reasonably be expected to see the same porosity.

Summarizing the computation process:

- Fiber and particulate debris are handled with the general form of the NUREG/CR-6224 correlation, Equation 3.7.2-1.

- Material properties are necessary – see Section 3.4.3 (Debris Characteristics) for material properties of material commonly encountered in PWRs.

- Knowing the debris quantities that are calculated to reach the sump screen, the mass ratio of particulates-to-fiber (η), the fiber density (ρ_f), and the average particulate density (ρ_p), and the theoretical bed thickness (ΔL_o) are determined.

- A compression factor [c] must be specified. This is an iterative process, with a value of 2.0 being a reasonable first approximation. (Adjust "c" thereafter in the direction of convergence. Alternatively, the bed thickness may be assumed and "c" derived from this.)

- The mixed-bed solidity (α_m) is next calculated from Equation 3.7.2-2.

- An overall, average value of S_v must be determined for the fibrous materials, each of the particulates and then an average for the overall debris mixture by Equation 3.7.2-7. If multiple fiber types are present, then each type should be included in the averaging process.

- The water properties (ρ and μ) are specified at the sump temperature at the time the head loss across the debris bed is calculated. Alternatively, a conservative approach would be to calculate the head loss using the lowest sump water temperature calculated over the entire time frame that the ECCS needs to function.

- The approach velocity will be known from the sump screen area and the ECCS flows through the screen.

- Substitution of all of the above information into Equation 3.7.2-1, in combination with iterative solution of Equations 3.7.2-3 and 3.7.2-4, yields the sump screen head loss and the actual debris-bed thickness, ΔL_m.

The head loss across a debris bed consisting of fibrous debris (no particulates) can be calculated with the general form of the NUREG/CR-6224 correlation, Equation 3.7.2-1, where the mass ratio of particulates-to-fiber (η) is set to zero. Given the presence of particulates from dirt/dust and possibly unqualified coatings, it would be unusual to have to analyze pure fiber bed head loss for a PWR. However, this case has application when interpreting experimental results, so it is mentioned for completeness.

3.7.2.3.1.2 RMI Debris Beds

The head loss for a RMI debris bed on the sump screen surface depends mainly on the accumulation at the sump screen and the type and size distribution of RMI debris. The key parameter needed to evaluate pure RMI head loss is the surface area of the RMI bed on the screen. The commonly accepted empirical correlation for RMI (Reference 6) is:

$$\Delta H = [1.56E\text{-}05/(K_t)^2]\ U^2\ A_{foil}/A_c \qquad \text{(Equation 3.7.2-8)}$$

where:

K_t is the interfoil gap thickness (ft)
ΔH is the head loss, (feet-of-water)
U is the sump screen approach velocity (ft/sec)
A_{foil} is the RMI foil surface area (ft^2)
A_c is the sump screen surface area (ft^2)

Extracted from Table 7-2 of NUREG/CR-6808, some values of K_t are listed below in Table 3-5. Other values of K_t are listed in Appendix K of the SER to the URG.

Table 3-5. Values of K_t from NUREG/CR-6808

Foil Type and Bed Type	K_t (feet)
2.5-mil SS (NRC large pieces)	0.014
2.5-mil SS (NRC small pieces)	0.010
1.5-mil Al (debris bed)	0.008
1.5-mil Al (debris bed)	0.006
2.5-mil SS (STUK flat pieces)	0.007
2.5-mil SS (1-mm dimple)	0.003

In Appendix K of the NRC SER to the BWROG URG, the NRC concluded that a value of K_t of 0.012 in the above general equation bounds the head loss data reasonably well for 2.5-mil SS RMI. Substituting this value of K_t into Equation 3.7.2-8, one obtains:

$$\Delta H = 0.108\ U^2\ A_{foil}/A_c \qquad \text{(Equation 3.7.2-9)}$$

Equation 3.7.2-9 accounts for experimental uncertainties, test repeatability variations, and variations in debris size and material types. As such, for 2.5-mil, SS foil, Equation 3.7.2-9 predicts the head loss across a pure RMI debris bed for PWR sump screens. The refinement guidance given in Section 4 provides further discussion of RMI head loss correlations.

3.7.2.3.1.3 Mixed Debris Beds (RMI, Fiber and Particulates)

A mixed debris bed of RMI, fiber and particulates is handled by superposition (Reference 6). First, the fiber-and-particulate head loss is determined using the methodology for fibrous debris beds with particulate discussed earlier in subsection 3.7.2.3.1.1. Next, the RMI head loss is determined using the methodology for RMI debris beds discussed above. These two head losses are then added to estimate the total head loss of a RMI, fiber, and particulate bed. This procedure is conservative, and the user need not be concerned with how the debris bed is formed.

The superposition of RMI and fiber may be overly conservative for cases where relatively large amounts of RMI and trace amounts of fiber (e.g., latent fiber) are estimated to be transported to the sump screen. Experiments have shown that fiber can become caught either within the voids of the RMI bed or at the surface of the RMI bed (which can have a significantly larger surface area and a lower approach velocity than the sump screen itself). For plants that have essentially all RMI, a relatively small amount of latent fiber could provide the quantity necessary to develop a thin bed, causing unacceptable or unrealistic results when added algebraically to the RMI head loss. More realistic methods for trace amounts of either RMI or fiber will be addressed in the refinement guidance of Section 4.

3.7.2.3.1.4 Calcium Silicate Insulation

Calcium silicate (Cal-Sil) is a granular insulation. It consists of fine particulate material that is chemically bonded and is also held together by a fine fibrous matrix. Experiments thus far indicate that it is best treated as a particulate material for head loss calculations. Test data will be required for specification of the appropriate particle sizes and surface-to-volume ratios to use in head loss analysis. At present, most of the head loss test data for Cal-Sil are privately held, the exception being the NRC/LANL/UNM Cal-Sil Test Report whose issuance is pending. Based on current information, the NUREG/CR-6224 correlation can be used according to the methods for fibrous debris beds with particulate if the application is limited to particulate mixtures containing up to about 20 percent Cal-Sil by mass. Additional head loss data for Cal-Sil are anticipated to be released by the NRC in the near future.

Cal-Sil is used in many PWRs and has different compositions. For example, it may contain diatomaceous earths, perlite, and/or asbestos fibers, and plant-specific characterization (via SEM analysis, at a minimum) is warranted to identify the specific composition, particle size range, and source of this material.

3.7.2.3.1.5 Microporous Insulation

Microporous insulation (e.g., MinK and Microtherm) is also a granular insulation and has been used in PWRs. The analyst is cautioned to ensure that the applicable material properties are used, since there may be significant variations in material properties from those suggested in the Debris Characteristics section. The Supplemental Guidance will provide additional background regarding the insights gained in the very limited series of head loss experiments available for review through May 2004.

3.7.2.3.1.6 Microporous and Fiber Debris

A limited series of head loss tests was performed with microporous debris in the presence of fibrous debris. These tests showed that the NUREG/CR-6224 correlation bounded the experimental data for all cases where the microporous-to-fiber mass ratio was less than about 20 percent. For mass ratios higher than about 20 percent, the NUREG/CR-6224 correlation was found to be potentially non-conservative.

The computation of the head loss of mixed microporous and fiber debris beds (where the microporous to fiber mass ratio is less than 20 percent) is the same as described earlier for a fiber and particulate bed. The currently available experimental database does not support a correlation for estimating the head loss across a debris bed composed of microporous and fibrous insulation where the microporous-to-fiber-mass ratio is more than 20 percent.

In the event that a debris bed composed of microporous and fibrous insulation (or calcium silicate and fiber, where the microporous-to-fiber (or the Cal-Sil-to-fiber) mass ratio is more than 20 percent), is calculated to form on the screens, the alternatives currently available for improving the sump screen performance include:

- Removal of microporous or calcium silicate insulation until the debris generation and transport analysis yields a debris mixture in which the particulate-to-fiber mass ratio is less than 20 percent.
- Use of a head loss correlation other than NUREG/CR-6224. (See the refinement guidance of Section 4 for potentially applicable head loss correlations.)
- Performance of head loss experiments using plant-specific debris mixtures, sump screen configuration, and thermal-hydraulic conditions.

Microporous or Calcium Silicate Debris Only

Based on results from a very limited series of experiments, microporous insulation debris or calcium silicate debris by itself has been shown to induce significant head losses. Tests have determined that the NUREG/CR-6224 correlation is unreliable for predicting the head loss of microporous insulation debris alone. The currently available experimental database does not support a correlation for estimating the head loss across a debris bed composed solely of microporous insulation debris.

Calcium silicate by itself has also been shown to induce high head losses (Reference 23). Preliminary indications are that the NUREG/CR-6224 correlation may fit the data if appropriate physical parameters are used in the correlation.

The alternatives currently available for improving sump screen performance for a debris bed on the screen composed of only microporous or calcium silicate insulation include:

- Removal of all granular insulation (e.g., Cal-Sil, MinK, Microtherm, etc.).
- Use of a head loss correlation other than NUREG/CR-6224.
- Performance of head loss experiments using plant-specific debris mixtures, sump screen configuration, and thermal-hydraulic conditions.

Granular Insulation and RMI Debris

Reference 23 suggests that the head loss for an RMI and calcium silicate debris bed will be relatively low, with increased head loss as the quantity of Cal-Sil debris increases. The expectation is that the same would also occur for all types of granular insulation (Min-K, Microtherm, and calcium silicate) and RMI debris beds. Mixtures of granular insulation, RMI, fiber, and other debris should be treated the same as mixed debris bed treatment discussed earlier with the limitations noted for calcium silicate and microporous insulation above.

3.7.2.3.2 Methodology Application Considerations

3.7.2.3.2.1 Total Sump Screen Head Loss

The total strainer head loss (TSHL) is the sum of the debris-bed head loss (DBHL) and the clean strainer head loss (CSHL).

TSHL = CSHL + DBHL

3.7.2.3.2.2 Evaluation of Breaks with Different Combinations of Debris

It is important to identify the break location that produces the highest debris bed head loss, i.e., the limiting break. The limiting break is not necessarily the break that generates the largest total quantity of debris. For example, a break that generates enough fiber and, after the transport considerations, deposits enough fiber on the screen to cause a thin bed may yield higher head losses in the presence of particulate than the break that generates more fiber (for the same quantity of particulate). As such, the analyst needs to evaluate a spectrum of breaks with different combinations of debris types to ensure that the mixture of debris on the screen that causes the highest head loss is identified.

3.7.2.3.2.3 Thin Fibrous Beds

For the reasons discussed in the preceding paragraph and as suggested in Revision 3 of RG 1.82, this methodology recommends that the head loss for a one-eighth-inch-thick fiber debris bed (including particulates) be evaluated for existing PWR sump screens.

For conditions of fiber and particulate present in the post-LOCA containment floor pool, as the fiber bed is deposited on the screen, particulate material will be trapped by the fiber, increasingly so as the fiber bed thickens. Once a fiber bed of approximately one-eighth-inch thickness is formed, if there is sufficient particulate debris, a low permeability granular layer of debris on top of the fiber bed will be formed. The head loss associated with the accumulation of mostly particulate debris on thin fibrous beds can be quite high, and surprisingly enough, greater than the head losses associated with much larger quantities of fiber and much thicker beds of debris. This apparently counterintuitive head loss phenomenon is known as the thin bed effect (TBE). The Supplemental Guidance will provide further discussions on the TBE.

It only takes a small quantity of fiber to facilitate TBE occurrence, and since it is difficult to make a defensible case that no fibers whatsoever are present in the containment, the possibility of forming a thin fibrous bed generally has to be evaluated for existing PWR screens. Additionally, given the uncertainties of debris generation and transport calculations, the total quantities of fiber calculated to reach the sump screens may be on the high side, hence the impact of a smaller quantity of fiber reaching the sump screen should be examined, i.e., the transport of only the fiber necessary to form a thin bed potentially being the limiting case. This methodology recommends that the head losses given a one-eighth-inch fiber bed (plus particulate) be calculated as a sensitivity analysis.

To analyze a thin fiber bed, a fiber quantity sufficient to form a bed one-eighth-inch thick should be determined to be available and if present could be deposited on the sump screen. The requisite quantity is easily calculated as 0.010-foot times the sump screen net area. The head loss computations are the same as described for fiber and particulate beds using the full value of particulate matter transported to the sump screen. (This would include latent debris such as dirt and concrete dust. It would also include any other fine particulate debris such as rust, inorganic zinc, epoxy fine material, etc.) It should be noted that the particulate layer is characterized by a very high sludge-to-fiber ratio; hence a limiting value for the compression is used. If under these conditions, the thin-bed head loss should exceed the NPSH margin, then the allowable particulate loading can be evaluated by reducing the particulate quantity until the calculated head loss is within the NPSH margin.

3.7.2.3.2.4 Sump Screen Submergence

For submerged screen sumps, the head loss computation methods presented herein are directly applicable. Submerged screens are characterized by having ambient pressure on one side of the screen, and the flow is driven by the pump. The limiting criterion for submerged screens occurs when the combined clean sump and debris bed head loss exceeds the NPSH margin.

For partially submerged screen sumps, the head loss computation methods presented herein are also directly applicable. Partially submerged screens are characterized by having the ambient pressure on both sides of the screen. In this case, the flow driver is the difference in fluid elevation between the two sides of the screen. As debris accumulates on the screen, the water level behind the screen falls and generates a pressure drop to allow the flow rate to be achieved. The limiting criterion for a partially submerged screen is when the debris bed accumulation on the screen reduces the flow to less than the flow requirements for the sump. Numerical simulations confirm that an effective head loss across a debris bed approximately equal to one-half of the pool height is sufficient to prevent adequate water flow. As such, for partially submerged sump screens, the methodology described herein should be used to estimate the pressure drop due to debris across the submerged sump screen area. The partially submerged sump screen will operate properly if the estimated head loss (in feet of water across the debris bed, when added to the clean screen head loss) is less than one-half the pool height.

3.7.2.3.2.5 Buoyant Debris

For fully submerged screens, buoyant debris is not considered a problem since it would not reach the sump screens. However, for partially submerged screens, the effects of buoyant debris should be considered. Note that the transport analysis may indicate that the quantity of buoyant debris reaching the sump screen is negligible, since trash racks and gates may largely prevent this.

For buoyant debris that is determined to reach a partially submerged screen, this baseline methodology recommends that the effective screen area be reduced by the thickness of the buoyant debris layer times the length of the covered perimeter, to the extent that it fully envelopes the screen. This is very conservative, since floating debris will have gaps and large pore space among pieces that will admit flow.

3.7.2.3.3 Methodology Limitations and Other Considerations

3.7.2.3.3.1 Flat Screen Assumption

The NUREG/CR-6224 correlation adopted in this methodology was developed mainly using data obtained in a closed loop that contained a vertical pipe section that housed a horizontally mounted flat screen. The flat screens yielded conservative data for the development of the NUREG/CR-6224 correlation because all debris was forced onto a very small screen in a small-scale test apparatus. In the case of alternate design screens (stacked disc, star, large passive, etc.) direct application of the NUREG/CR-6224 correlation may yield overly conservative results (Reference 17). For these alternate geometry screens, independent head loss correlations should be developed based on actual design configurations, debris loads, and test data to reduce conservatism.

3.7.2.3.3.2 Non-Uniform Deposition on Sump Screen Surfaces

PWR sump screens can have vertical and inclined orientation. On a vertical screen, there is greater chance for non-uniform deposition of debris, which will usually lead to lower head losses because of thin spots in the debris bed. Body forces also tend to shear the bed from the screen, also a mitigating factor. For these reasons, using the uniform deposition assumption for vertical screens is a conservative approach. Similar statements can be made for curved surfaces such as horizontally oriented, cylindrical strainer designs, since body forces in the debris bed essentially act in the opposite direction to the suction forces over a significant portion of the strainer area. An inclined, flat surface is less limiting than a horizontal surface; therefore, the uniform deposition assumption again should be conservative.

3.7.2.3.3.3 Very Thin Fiber Beds

This section pertains to the regime where fiber loading is less than that required to form a thin bed. The NUREG/CR-6224 head loss correlation was developed and validated for debris that is uniformly distributed on the screen surface. However, experiments have shown that very thin fibrous beds (with a thickness of less than one-eighth inch) are characterized by large scale non-uniformities on the screen and negligible head losses. For fibrous debris bed less than one-eighth inch thick, the NUREG/CR-6224 head loss correlation significantly overpredicts the experimentally determined head loss and should not be used. Instead, it is appropriate to consider the head loss across fibrous debris beds of less than one-eighth inch to be negligible.

3.7.2.3.4 Sample Calculations

The following examples demonstrate the use of the head loss equations with the debris sources specified in Section 3.4.3 of this document and typical plant conditions. These calculations assume steady-state conditions at final debris loading with steady ECCS flows and a simple, flat-plate strainer geometry.

3.7.2.3.4.1 Fiber and Particulate Debris Bed

<u>Flow Conditions</u>

These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	9000	gpm
Temperature (T)	=	170	°F
Fluid density (ρ)	=	60.80	lbm/ft^3
Fluid viscosity (μ)	=	2.51E-04	lbm/ft/sec

<u>Screen Parameters</u>

These are obtained from screen design drawings and ECCS flow rate.

Effective surface area (A)	=	300	ft^2
Screen approach velocity (U)	=	0.067	ft/s

Debris Types/Quantities at Screen

These are obtained from Debris Characteristics (Section 3.4.3), Latent Debris (Table 3-4) and the Transport Analysis (Section 3.6).

Nukon fiber	=	129	ft^3	
Latent fiber	=	8.84	ft^3	$\Leftarrow$ 62.4/2.4 * 0.34 ft^3
Latent dirt-dust	=	33.51	lbm	
Qual-epoxy	=	329	lbm	
Unqual. coatings	=	2625	lbm	

Debris Characteristics

- Nukon

Theoretical packing density (ρf)	=	2.4	lbm/ft^3	
Fiber diameter (D)	=	$2.33 * 10^{-5}$	ft (use LDFG)	
Surface to volume ratio (Sv)	=	$1.717 * 10^5$	ft^{-1}	$\Leftarrow 4 / 2.33 * 10^{-5}$ ft^3
Mass of fiber (m_f)	=	309.6	lbm	$\Leftarrow$ 129 ft^3 * 2.4 lbm/ft^3
Fiber density	=	175	lbm/ft^3	
Fiber volume	=	1.77	ft^{-3}	$\Leftarrow$ 309.6 lbm / 175 lbm/ft^3

- Latent fiber

Theoretical packing density (ρf)	=	2.4	lbm/ft^3	
Fiber diameter (D)	=	$2.33 * 10^{-5}$	ft	
Surface to volume ratio (Sv)	=	$1.717 * 10^5$	ft^{-1}	$\Leftarrow 4 / 2.33 * 10^{-5}$ ft^3
Mass of fiber (m_f)	=	21.22	lbm	$\Leftarrow$ 8.84 ft^3 * 2.4 lbm/ft^3
Fiber density	=	62.4	lbm/ft^3 (Table 3-1)	
Fiber volume	=	0.34	ft^{-3}	$\Leftarrow$ 21.22 lbm / 62.4 lbm/ft^3

- Latent dirt/dust

Particle density	=	100	lbm/ft^3	
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft	
Surface to volume ratio (Sv)	=	$1.829 * 10^5$	ft^{-1}	$\Leftarrow 4 / 2.33 * 10^{-5}$ ft^3
Particle volume	=	0.335	lbm	$\Leftarrow$ 8.84 ft^3 * 2.4 lbm/ft^3

With respect to qualified coatings in the ZOI, a relatively high damage pressure was justified in earlier sections of this document. However, the demonstration calculations will use a spherical ZOI with radius of 10 feet, for a surface area of 1256.6 ft^2. The qualified coatings thickness is taken to be 0.009 inch. For unqualified coatings, a thickness of 0.003 inch is used, and 30,000 ft^2 is the assumed coverage. In both cases, the coating particles are conservatively assumed to be spherical with diameter equal to 10 µm. The coatings material is assumed to be inorganic zinc (IOZ) in both cases.

- Qualified epoxy

Particle density	=	350	lbm/ft^3 (IOZ-equivalent)
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1} $\Leftarrow 6 / 3.28 * 10^{-5}\ ft^3$
Particle volume	=	0.94	lbm $\Leftarrow$ 329 lbm / 350 lbm/ft^3

- Unqualified epoxy

Particle density	=	350	lbm/ft^3 (IOZ-equivalent)
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1} $\Leftarrow 6 / 3.28 * 10^{-5}\ ft^3$
Particle volume	=	7.50	lbm $\Leftarrow$ 2625 lbm / 350 lbm/ft^3

- Average fiber

Total fiber volume	=	2.11	ft^3
Total fiber mass	=	330.82	lbm
Ave. fiber density	=	156.86	lbm/ft^3
Ave. surface to volume ratio (S_v)	=	$1.717 * 10^5$	ft^{-1}

- Average particulate

Total particle volume	=	8.775	ft^3
Total particle mass	=	2987.5	lbm
Ave. particle density	=	340.46	lbm/ft^3
Ave. surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1}

- Average debris

Total particle volume	=	8.775	ft^3
Ave. surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1}
Total fiber volume	=	2.11	ft^3
Surface to volume ratio (S_v)	=	1.717 I * 10^5	ft^{-1}
Ave. debris surface to volume ratio (S_v)	=	$1.8078 * 10^5$	ft^{-1}

Debris Bed Equations:

- Theoretical debris bed thickness (ΔL_o)

Total volume of fiber divided by screen area = 5.51 inches

- Particulate to fiber mass ratio (η)

  Mass of particles divided by mass of fiber = 9.03

- Actual bed thickness (ΔL_m)= 2.72 inches

Assume a value for the bed thickness and iterate until Equations 3.7.2-3 and 3.7.2-4 converge on approximately the same number. Computer solution may be required.

Head loss across debris bed (ΔH) = 17.80 feet H_2O	(using Equation 3.7.2-1)
Mixed debris bed solidity (αm) = 0.16	(using Equation 3.7.2-2)
Head loss volumetric compression (c) ≈ 2.03	(using Equation 3.7.2-3)
Head loss volumetric compression (c) ≈ 2.03	(using Equation 3.2.5-4)

Equations 3.7.2-3 and 3.7.2-4 have converged within ~1 percent of each other, which is considered acceptable convergence. Therefore, the head loss is calculated as 17.80 feet of water.

The mixed debris bed solidity should be less than or equal to 0.20, therefore OK.

3.7.2.3.4.2 Fiber Debris Bed

No sample calculation is provided since a pure fiber debris bed would be unusual, given the coatings particulate debris in the ZOI, latent debris, the presence of dirt/dust, and other possible sources of particulates such as ablated concrete. However, should a fiber-only debris-bed head loss need to be calculated, the process would be the same as for fiber and particulate except that the particulate quantities would be set to zero.

3.7.2.3.4.3 RMI Debris Bed

<u>Flow Conditions:</u>

These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	9000	gpm
Temperature (T)	=	170	°F
Fluid density (ρ)	=	60.80	lbm/ft^3
Fluid viscosity (μ)	=	2.51E-04	lbm/ft/sec

Screen Parameters:

These are obtained from screen design drawings and ECCS flow rates.

Effective surface area (A)	=	300	ft^2
Screen approach velocity (U)	=	0.067	ft/s

Debris Types/Quantities:

These are obtained from the Debris Characteristics (Section 3.4.3) and Debris Transport Analysis (Section 3.6).

2.5-mil SS RMI	=	4387.5	$ft^2 \Leftarrow 11{,}250\ ft^2 * 0.39$ T.F.

Debris Bed Equations:

The head loss correlation for RMI is taken from the RMI debris bed discussion in subsection 3.7.2.3.1.2.

$$\Delta H = 0.108\ U^2\ (A_{foil}/A_c)$$

where,

ΔH = the head loss across the RMI bed (ft-water)

U = the approach velocity to the screen (ft/s)

A_{foil} = the surface area of the RMI foils (ft^2 – nominal)

A_c = the strainer circumscribed area (ft^2)

Substituting the above plant-specific parameters

$$\Delta H = 0.108\ (0.067)^2\ (4387.5/300)$$

$$= 0.007 \text{ ft-water} \cong 0.01 \text{ ft-}H_2O$$

3.7.2.3.4.4 Mixed Debris Beds (RMI, Fiber, and Particulates)

The head loss of a mixed fiber, particulate, and RMI debris bed is the addition of the fiber-and-particulate head loss to the RMI head loss. For example, if the quantities of debris were as in the totals of the two preceding calculations, then the total mixed RMI and fibrous debris bed head loss would be:

$$\Delta H_{RMI} = 0.01 \text{ ft-water}$$

$$\Delta H_{Fiber + Particulate} = 17.80 \text{ ft-water}$$

hence,

$\Delta H_{RMI+\ Fiber\ +\ Particulate}$ = 17.81 ft-water (We can neglect the RMI in this case.)

3.7.2.3.4.5 Thin-Bed of Fiber and Particulate Debris

Flow Conditions:

These are obtained from plant design documents and NPSH calculations.

ECCS flow rate (Q)	=	9000	gpm
Temperature (T)	=	170	°F
Fluid density (ρ)	=	60.80	lbm/ft^3
Fluid viscosity (μ)	=	2.51E-04	lbm/ft/sec

Screen Parameters:

These are obtained from screen design drawings and ECCS flow rate.

Effective surface area (A)	=	300	ft^2
Screen approach velocity (U)	=	0.067	ft/s

Debris Types/Quantities:

As a starting point, use plant-specific quantities of fine particulate and latent debris.

Provided that sufficient fiber is available, the fiber quantity is specifically selected to create a thin bed. Nukon is assumed for this example, although latent fiber could be used if a sufficient amount is present.

Nukon fiber	=	3.125	$ft^3 \Leftarrow 0.125''/12 * 300\ ft^2$
Dirt Dust	=	33.51	lbm
Qual-epoxy	=	329	lbm
Unqualified coatings	=	2625	lbm

Debris Characteristics:

- Nukon

Theoretical packing density (ρf)	=	2.4	lbm/ft^3
Fiber diameter (D)	=	$2.33 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.717 * 10^5$	$ft^{-1} \Leftarrow 4 / 2.33 * 10^{-5}\ ft^3$
Mass of fiber (m_f)	=	7.5	$lbm \Leftarrow 3.125\ ft^3 * 2.4\ pcf$
Fiber density	=	175	lbm/ft^3
Fiber volume	=	0.043	$ft^{-3} \Leftarrow 7.5\ lbm / 175\ lbm/ft^3$

- Latent dirt/dust

Particle density	=	100	lbm/ft^3
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1} ⇐ $6 / 3.28 * 10^{-5}\ ft^3$
Particle volume	=	0.335	lbm ⇐ $33.51\ ft^3 / 100\ lbm/ft^3$

- Qualified epoxy

Particle density	=	350	lbm/ft^3 (IOZ-equivalent)
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1} ⇐ $6 / 3.28 * 10^{-5}$ ft
Particle volume	=	0.94	lbm ⇐ $329\ lbm / 350\ lbm/ft^3$

- Unqualified coatings

Particle density	=	350	lbm/ft^3 (IOZ-equivalent)
Particle diameter (D)	=	$3.28 * 10^{-5}$	ft
Surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1} ⇐ $6 / 3.28 * 10^{-5}$ ft
Particle volume	=	7.5	lbm ⇐ $2625\ lbm / 350\ lbm/ft^3$

- Average particulate

Total particle volume	=	8.775	ft^3
Total particle mass	=	2987.5	lbm
Ave. particle density	=	340.46	lbm/ft^3
Ave. surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1}

- Average debris

Total particle volume	=	8.775	ft^3
Ave. surface to volume ratio (S_v)	=	$1.829 * 10^5$	ft^{-1}
Total fiber volume	=	0.043	ft^3
Surface to volume ratio (S_v)	=	$1.717 * 10^5$	ft^{-1}
Ave. debris surface to volume ratio (S_v)	=	$1.82847 * 10^5$	ft^{-1}

Debris Bed Equations:

- Theoretical debris bed thickness (ΔL_o)

  Total volume of fiber divided by screen area = 0.125 inch

- Particulate to fiber mass ratio (η)

  Mass of particles divided by mass of fiber = 398.34

- Actual bed thickness (ΔL_m) = 1.764 inches

  Sum the fiber and particulate volumes. Multiply by 12 and divide by the product of the (solidity * screen net area) Limiting solidity value of 0.20 is recommended.

(Using Equation 3.2.5-1) Head loss across debris bed (ΔH) = 19.27 ft-H_2O

(Using Equation 3.2.5-2) Mixed debris bed solidity (α_m) = 0.20

The calculated head loss is 19.27 feet of water via iterative solution. Computational tools may be required. Since the calculated head loss of the thin bed exceeds the NPSH margin at most plants, parametric calculations can be performed to determine the allowable particulate quantities at the sump screen(s).

3.7.2.3.4.6 Microporous Insulation

As noted in the microporous insulation discussion in subsection 3.7.2.3.1, the currently available experimental data can only support the head loss calculations of microporous insulation debris in the presence of fibrous debris provided the mass ratio of microporous insulation-to-fiber is less than 20 percent. In these cases, the microporous insulation debris is treated as a particulate and the equations and methods for fibrous and particulate head loss are used (see example of the fibrous and particulate debris bed calculation above).

3.7.2.3.4.7 Determination of Requisite Sump Screen Size

If, through the evaluation of the debris head loss, the existing screen does not provide sufficient surface area, the calculations provided within this methodology can be utilized with little or no modification to determine the amount of surface area required.

The key assumption in the head loss correlations provided is homogeneous debris accumulation on a flat plate. As noted in the very thin fiber bed discussion in subsection 3.7.2.3.3.3, different screen orientations and configurations can provide different debris accumulation profiles and take advantage of uneven debris distribution and flow redistribution. In these cases, the head loss correlations provided in this methodology may yield overly conservative results. As such, adjustments to the head loss correlation could be made based on experimental test data applicable to the actual sump screen orientation and configuration. Some test data exist for vertical screens (see Reference 24), but applicability of the test data always has to be assessed. In some cases, plant-specific testing may be required to reduce conservatism. Suggested refinements are further outlined in the Supplemental Guidance.

3.7.2.3.4.8 Calcium Silicate

Informal results on the NRC/Los Alamos National Laboratory (LANL) calcium silicate testing at the University of New Mexico (UNM) were presented in February 2003 (Reference 23). This presentation did not provide any quantitative guidance with respect to use of the NUREG/CR-6224 correlation with Cal-Sil debris mixtures. A recent LANL/NRC/UNM paper (Reference 23) has provided more detailed test results. The formal NRC test report on this program is not yet available.

Reference 23 has been reviewed, and some observations are provided. With respect to the calcium silicate tests with Nukon fiber, the principal comment is that these results will have to be applied very carefully on a plant-specific basis. For example, the researchers operated their test apparatus at very high flow rates, which induced high approach velocities that compressed the debris beds to the compression limit of the granular debris. When the flow was reduced, the compressed bed did not relax, nor did it release the trapped particles. Hysteresic effects were observed, for which head losses were actually greater at lower flows. Then, the surface-to-volume ratio was adjusted such that the NUREG/CR-6224 correlation conservatively predicted the hysteresic effects. For some plants, this testing does not represent prototypical behavior, and it is excessively conservative. It also suggests the troubling conclusion that there is no benefit to throttling the ECCS flows to reduce sump screen head loss with Cal-Sil, which for some plants again may not be true.

Based on the research procedures described above, Reference 23 concludes that $S_V = 550{,}000\ ft^{-1}$ is an appropriate value for the specific type of Cal-Sil that was tested. The researchers further recommend that this value be conservatively enhanced for safety analyses. Our observation is that this procedure will be excessively conservative for many plants, depending on the type(s) of Cal-Sil present in these plants and on the sump screen approach velocities. Therefore, the results of Reference 23 should be applied with extreme caution.

The researchers applied similar techniques to the test with fiber, dirt and concrete dust in Reference 23. Therefore, the recommended value of $S_V = 190{,}000\ ft^{-1}$ is also considered too conservative.

Reference 23 itself mentions that the LANL Test Report, LA-UR-03-0471, should be consulted for final recommendations once it is issued. On April 17, 2004, the PWR Industry became aware that Los Alamos published LA-UR-04-1227, "GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation." A review of that document has been initiated to help assess what, if any, further guidance regarding treatment of calcium silicate might be supported by the tests reported.

4 ANALYTICAL REFINEMENTS

The Baseline Methodology described in Section 3 incorporates conservatisms in the analytical approach to evaluating post-accident sump performance. Identified in this section are refinements that may be implemented to those analytical approaches to provide for more realistic but still conservative evaluations.

4.1 INTRODUCTION

To facilitate its applicability to all PWRs, the Baseline Methodology utilized conservative analytical approaches to evaluating the five main topics associated with post-accident sump performance:

1. Break selection
2. Debris generation
3. Latent debris
4. Debris transport
5. Head loss

With the exception of latent debris, refinements to the analytical approaches have been developed that, if applied, provide for more realistic, but still conservative, post-accident sump performance evaluations.

4.2 METHOD DESCRIPTION

Described within this section are refinements to three of the five analytical topics that comprise the Baseline Methodology. Although no refinements to break selection and latent debris guidance are offered, they are included in this section for completeness.

4.2.1 Break Selection

On July 19, 1987, the NRC issued Generic Letter 87-11, "Relaxation in Arbitrary Intermediate Pipe Rupture Requirements." The Generic Letter informed licensees that the NRC had finalized a revision to Branch Technical Position MEB 3-1 of the Standard Review Plan Section 3.6.2 in NUREG-0800. The revision eliminated all dynamic effects (missile generation, pipe whipping, pipe break reaction forces, jet impingement forces, compartment, subcompartment and cavity pressurizations, and decompression waves within the ruptured pipe) and all environmental effects (pressure, temperature, humidity, and flooding) resulting from arbitrary intermediate pipe ruptures.

Arbitrary intermediate pipe ruptures, which previously were specified in B.1.c.(1)(d) of MEB 3-1 for ASME Code Class 1 piping and in B.1.c.(2)(b)(ii) of MEB 3-1 for ASME Code Class 2 and 3 piping, are now no longer mentioned or defined in MEB 3-1. Besides the relaxation in requirements relating to arbitrary intermediate pipe ruptures, the revised Standard Review Plan Section 3.6.2 updated the citations to the ASME stress limits to achieve consistency with current practices, and introduced other minor changes. The requirements for postulated terminal end pipe ruptures, postulated intermediate pipe ruptures at locations of high stress, and high usage factor for leakage cracks were retained in the revision to MEB 3-1.

Consistent with a plant's licensing basis, MEB 3-1 may be used to select break locations for evaluating post-accident sump operability. The application of MEB 3-1 is justified for this purpose as it focuses attention on high stress and fatigue locations, such as at the terminal ends of a piping system at its connection to the nozzles of a component. The junction of a steam generator and the primary system piping is included as such a location. It is the industry experience that the steam generator is the largest source of insulation debris from a postulated pipe rupture. Furthermore, if multiple insulation types are used inside containment, they are often used on steam generators. Therefore, the application of MEB 3-1 is considered appropriate and conservative for selecting break locations.

4.2.2 Debris Generation

4.2.2.1 Zone of Influence

The zone of influence (ZOI) is defined as the volume about the break in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coatings, and other materials within the zone.

For the baseline calculation, it is recommended that the boundary of the ZOI be assumed to be spherical, with the center of the sphere located at the break site. The use of a spherical ZOI is intended to encompass the effects of jet expansion resulting from impingement on structures and components. Two analytical refinements to the definition of the ZOI for insulation materials are recommended, as documented below. No refinements are offered in the definition of the ZOI for coatings.

4.2.2.1.1 Method 1: Debris-Specific Spherical ZOIs

This method is similar to that recommended in Section 3.4 of this document, in that the ZOI is defined as a sphere with its origin at the break site. However, Section 3.4 recommends defining one spherical ZOI for each break site, based on the insulation with the lowest destruction pressure.

It is recommended that the ZOI definition be refined by assigning multiple ZOIs to each break site, with each corresponding to the destruction pressure of one insulation species located near the break site. Using this method still incorporates the conservatism and ease of use of a spherical ZOI, but more realistically models the destruction of multiple insulation types. Calculations are performed in the same way as those recommended in Section 3.4, including the treatment of robust barriers.

Definition of Spherical ZOI

To determine the radius of the spherical ZOI needed to represent the effects of the jet originating from a postulated pipe break, the ANSI/ANS 58.2-1988 standard (Reference 3) was used, as described in Section 3.4 of this document. The basis for the use of the equivalent spherical ZOI is also described in Section 3.4 of this document.

Equivalent spherical ZOI calculations were performed and documented for values of isobars corresponding to destruction pressures of several types of insulation. Table 3-1 summarizes these insulation types and the applicable ZOI, expressed as the ratio of the ZOI radius to the break diameter, for which the calculations were performed. The calculations summarized in Table 3-1 make no changes in insulation destruction pressures based on the differences between dry or saturated steam jets and flashing, as described in Section 3.4 of this document.

The ZOI and Robust Barriers

The effects of robust barriers on the ZOI are modeled in the same way as recommended in Section 3.4.

Evaluating Debris Generation Within the ZOI

Once the ZOI for each insulation type has been determined, calculate the amount of debris generated within each ZOI, then sum the individual contributions to determine the debris source term. Information about the type, location and amount of debris sources within the containment is obtained from plant drawings and the results of a condition assessment walkdown such as described in NEI 02-01 (Reference 2). The characterization of the debris (transport characteristics) is evaluated using the debris transport guidance in Sections 3.6 and 4.2.4.

4.2.2.1.2 Method 2: Direct Jet Impingement Model

Whereas Section 3.4 and the refinement described above use a spherical ZOI to model the region of insulation destruction, it is also possible to define the ZOI by modeling two freely-expanding jets, each originating at one end of the DEGB. It is recommended that if this method is used, the ANSI/ANS 58.2-1988 standard be used to determine the jet geometry.

Definition of ZOI

The ANSI/ANS 58.2-1988 standard (Reference 3) provides the information necessary to map the constant-stagnation-pressure contours (isobars) for jets originating from a postulated pipe break. Appendices B, C, and D of Reference 3 provide the guidance necessary to determine the geometry of a freely-expanding jet. Guidance is provided for jets originating from a variety of reservoir conditions, including subcooled conditions. Using this method to define a ZOI requires a high degree of rigor in determining what stagnation pressure each insulation type is subjected to.

The guidance in Reference 3 was used to determine the geometry of a jet originating from a postulated break in a PWR piping system. A subcooled reservoir and flashing break flow were assumed for the calculations as detailed below. The following steps were followed in performing the calculations:

1. The mass flux from the postulated break was determined using the Henry-Fauske model, as recommended in Appendix B, for subcooled water blowdown through nozzles, based on a homogeneous non-equilibrium flow process. No irreversible losses were considered.

2. The initial and steady-state thrust forces were calculated based on the guidance in Appendix B of Reference 3, and the postulated reservoir conditions detailed below.

3. The jet outer boundary and regions were mapped using the guidance in Appendix C, Section 1.1, of Reference 3 for a circumferential break with full separation. The input to the equations from Appendix C for the thermodynamic conditions at the asymptotic plane was calculated using principles of thermodynamics and the postulated conditions in the reservoir.

4. A spectrum of isobars was mapped using the guidance in Appendix D of Reference 3.

5. The volume encompassed by the various isobars was calculated using a trapezoidal approximation to the integral.

The jet expansion calculations were based on the following conditions:

1. A circular break geometry was used for the calculations. This break geometry is representative of both a postulated DEGB of primary piping as well as the DEGB of piping attached to the RCS. The complete breaking of a pipe, either primary piping or piping attached to the RCS, provides for a maximum debris generation volume as there are two ends of the break to release fluid.

2. Fluid reservoir conditions of 2250 psia and 540°F were used for the calculations. The corresponding stagnation enthalpy and subcooling used in the calculations are 547.2 Btu/lbm and 102.7°F, respectively. These conditions are intended to represent a PWR cold leg at full power and provide for a conservatively large ZOI compared to hot-leg conditions at power operations.

3. Ambient pressure of 14.7 psia was used. This is conservative as no credit is taken for containment backpressure (the increase in containment pressure that would result from the release of mass and energy into the containment as a result of the postulated break).

The results of the isobar mapping calculations as well as an example of a plotted isobar are contained in Appendix D. For both the plot and table, the radius of the isobar is defined as a function of the axial distance from the break site. Using symmetry about the longitudinal axis, it is possible to define the three-dimensional constant-stagnation-pressure surface.

The ZOI and Robust Barriers

The effects of robust barriers on the ZOI are modeled in the same way as recommended in Section 3.4.

Evaluating Debris Generation Within the ZOI

Once the ZOI for each insulation type has been determined, calculate the amount of debris generated within each ZOI, then sum the individual contributions to determine the debris source term. Information about the type, location, and amount of debris sources within the containment is obtained from plant drawings and the results of a condition assessment walkdown such as described in NEI 02-01 (Reference 2). The characterization of the debris (transport characteristics) is evaluated using the debris transport guidance in Sections 3.6 and 4.2.4.

4.2.2.2 Debris Characteristics

This section provides data that may be used with the logic and procedures presented in Section 3.4.3 to conservatively predict the characteristics of debris generated as a result of a LOCA.

4.2.2.2.1 Fibrous Insulation

Physical characteristics of fibrous materials (except calcium silicate), are identified in Table 3-2. Destruction pressures for common insulation and coating materials are provided in Table 3-2. The damage characteristics of additional materials are based on extrapolation of test data that are provided in Table 3-1. Not all generated fibrous debris needs to be assumed to be of a transportable size. The specifics of transportability are discussed in the debris transport section.

Fire barrier materials are addressed separately in subsection 4.2.2.2.5.

For some plant sites, it may be desirable to use a bounding, simplifying assumption for the debris size distribution. It would always be acceptable to conservatively assume that all debris is reduced to fine particles. It is also acceptable to assume a more conservative (biased toward smaller pieces) distribution than that presented in Section 3.4.3.2.

Utilities should also review their design documentation for additional information regarding debris generation characteristics of insulation used in their plant. For example, the NRC has previously reviewed and issued an SER on Nukon insulation and its consequential effect on ECCS operation post-accident (Reference 26).

4.2.2.2.2 Reflective Metallic Insulation (RMI)

RMI debris is assumed to be generated within the ZOI. Typically, RMI is installed in pre-fabricated cassettes that conform to the piece of equipment being insulated. Break jet impingement can dislodge RMI and possibly destroy cassettes, creating smaller pieces of debris.

The following information should be used to evaluate the potential for debris generation from RMI cassettes:

- Latch mechanism types and characteristics
- Pressure at which destruction of the cassettes will occur
- Differences in destruction pressure for different insulation brands and types
- Modes of insulation detachment and destruction
- Destruction of insulation adjacent to the break site

RMI destruction regimes are defined as:

- Dislodged cassettes
- Damaged cassettes (individual foils produced)
- Complete destruction (shredded and crumpled foils). This occurs for RMI located on the section of piping where the break occurs and on sections of pipe and components located within six pipe diameters of the break site.

The destruction pressures for RMI are given in Table 3-1. The recommended debris size distribution is given in Reference 27.

4.2.2.2.3 Coatings

All coatings need to be identified as DBA-qualified/acceptable or non-DBA qualified/ unacceptable. Guidance on evaluating coatings is given in Reference 27.

4.2.2.2.3.1 Coatings Within the ZOI

Within the ZOI of the postulated break, all coating materials (DBA-qualified and non-DBA-qualified) will be assumed to fail and will therefore contribute to the debris source term.

- The type(s) of coating systems within the ZOI should be identified and documented. If multiple coating systems have been applied to surfaces within the ZOI, the properties of the coating system that produces post-accident debris most detrimental to the containment sump should be used in subsequent transport and sump clogging analyses. Representative physical characteristics of the failed coating materials within the ZOI are shown in Table 3-2

4.2.2.2.3.2 Coatings Outside the ZOI

- DBA-qualified coatings outside the ZOI, when properly maintained, do not fail and therefore do not contribute to the debris source term.

- Non-DBA-qualified coatings outside the ZOI may disbond from the substrate and contribute to the debris source term.

- Non-DBA-qualified coatings that are potential debris sources include coatings on equipment permanently stored in containment or temporarily left in containment after an outage.

- In the absence of vendor-generated or plant-specific data, all non-DBA-qualified coatings should be assumed to fail and therefore be considered in the debris source term.

- Vendor or plant-specific data or experience may support using less than complete (100 percent) failure of non-DBA-qualified coatings in the debris source term. Additionally, an industry research project is being conducted by the Electric Power Research Institute (EPRI) PSE in 2003/2004 concerning the failure of original equipment manufacturer (OEM) non-DBA-qualified/unacceptable coatings in the PWR DBA environment to provide additional data on this topic.

- The type(s) of coating systems outside of the ZOI should be identified and documented. If individual non-DBA-qualified coating systems used outside of the ZOI are not identified, the properties of the non-DBA-qualified coating system that produces post-accident debris most detrimental to the containment sump should be used in subsequent transport and sump clogging analyses. The following types of coatings are commonly found within PWR containments: inorganic zinc (IOZ), epoxy, epoxy phenolic, and alkyd. Representative physical characteristics of failed coating materials outside of the ZOI are shown in Table 3-2.

4.2.2.2.4 Tape, Tags and Stickers

All tape, tags and stickers located in the ZOI are assumed to fail and contribute to the debris source term. This includes, but is not limited, to materials that are qualified for service in DBA conditions. Duct, electrical, masking, and grip tape are potential debris sources but other types of adhesive tape can be used inside containment. Equipment labels and tags secured by adhesives or other means are also potential sources of debris. All tape and stickers located in the ZOI will be assumed to be destroyed, creating small pieces and or fibers.

Tape, tags and stickers should be incorporated in licensees' FME programs to minimize the amount present inside containment. A licensee's FME program should be considered when performing the plant-specific evaluation.

All non-qualified tape and stickers outside the ZOI are assumed to fail unless a technical justification to exclude them from the source term is available. Non-soluble tape, stickers, and tags secured by adhesives located outside the ZOI will be assumed to fail by peeling away from the surface to which they are attached. Soluble tape, stickers, and tags secured by adhesives or other means will be assumed to dissolve under the action of containment sprays or other sources of water.

The size distribution of the debris produced by tape, tags and stickers should be evaluated on a case-specific basis. The properties of the materials in question should be used to determine a conservative debris size distribution (i.e., biased toward smaller, transportable forms). It is conservative to assume that all debris created from tape and stickers is reduced into fine or small pieces or individual fibers.

It is noteworthy that for some plant-specific applications, the amount of debris produced by tape, tags and stickers will be quite small compared to the contributions from other materials inside containment. In these cases, it may be possible to neglect the contribution of tape, tags and stickers to the debris source term.

4.2.2.2.5 Fire Barrier Materials

Fire barrier material may be a source of debris inside containment. This includes board material, blanket material, and foam material. Fire barrier materials within the ZOI are to be evaluated as potential debris sources.

Fire barriers consist of many types of insulation and other materials. Many of the materials are similar or identical to those used to insulate RCS piping and components. These fire barrier materials may be treated in the same way as their counterparts used in other applications inside containment (i.e., the same destruction pressures can be used). However, differences in attachment, encapsulation, and construction of the fire barrier materials compared to RCS insulation should be accounted for when determining the amount of debris generated from materials that are also used in other applications.

Fire barrier materials are typically unencapsulated. The destruction pressures for these non-encapsulated blanket materials will be lower than encapsulated RCS insulation of comparable composition.

For materials that are unique to fire barrier applications and do not have supporting test data, a destruction pressure equal to that of low-density fiberglass may be assumed. Available destruction information for fire barrier and other materials that might be found inside typical PWR containments is given in Table 4-1.

A ZOI for fire barrier materials can then be constructed. This ZOI will be conservative since many fire barrier materials, such as fibrous boards, will have a higher destruction pressure than low-density fiberglass.

As an alternative, engineering judgment can be used to assign destruction pressures based on similarities in material properties between the fire barrier materials and materials for which destruction pressures are known. There is little information available regarding the destruction of board-type insulation. In most cases, the destruction pressure for the blanket-type insulation can be assumed to be the same as for low-density fiberglass piping insulation.

Specific fire barrier materials include:

- Marinite board which may be included in the debris is generated within the ZOI. According to NUREG/CR-6772, a large amount of plastic deformation is necessary to break Marinite board apart. Therefore, Marinite board is assumed to be destroyed within the ZOI but left intact outside the ZOI. All destroyed Marinite board can be assumed to be broken into large chunks.

- Kaowool blanket and mineral wool debris are destroyed in the ZOI. Assume the same destruction data for fiberglass or Nukon.

- Silicone foam debris is assumed to be destroyed within the ZOI. As with some other types of fire barrier, destruction information is needed for silicone foam insulation.

4.2.2.2.6 Miscellaneous Debris Sources

This section discusses the generation of debris from sources inside containment other than RCS and fire barrier insulations tape, tags, and stickers. There are many miscellaneous debris sources inside containment. Some common sources are discussed in the following sections. Due to the variations in containment design and size from unit to unit, many miscellaneous sources can be evaluated on a plant-specific basis. It is not appropriate for the licensees to use their FME programs to entirely eliminate sources of miscellaneous debris.

Candidate miscellaneous debris sources that should be evaluated on a plant-specific basis are listed below. For each potential debris type considered, debris generation resulting from jet impingement and washdown effects should be considered.

- Fabric equipment covers
- Fire hoses
- Ropes
- Ventilation system filters
- Cloth
- Wire ties
- Plastic sheeting
- Rust from unpainted surfaces
- Scaffolding
- Auxiliary equipment left inside containment
- Caulking
- Mastic or filler materials
- Fibrous material from lead blankets
- Radiation protection signage
- Operations tags

Consideration that should be given to tape, tags and stickers as debris sources is discussed in Section 4.2.2.2.4.

Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments(Note 6)

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft^3)	Material Density (lb/ft^3)	Characteristic Size	
					µm	Inch
Calcium Silicate	1. Al clad, SS banding seam @ 180° 2. Al clad, SS banding seam @ 0° 3. Al clad, SS banding seam @ 45°	1. 64(Ref. 27) 2. 50(Ref. 27) 3. 24(Ref. 27)	14.5	144(Ref.11)	5 µm mean particle size (2 to 100 µm range) (Ref.11)	20E-05
Calcium Silicate	Generic seam orientation	20	14.5	144(Ref.11)	5 µm mean particle size (2 to 100 µm range) (Ref.27)	20E-05
Newtherm	Clad with either SS or aluminum with high-strength stainless steel bands and closures		16.2	144(Ref.11)	5 µm mean particle size (2 to 100 µm range) (Ref.11)	20E-05
Microporous Insulation						
Min-K	1. Blanketed, unjacketed 2. Blanketed, jacketed w/SS band and latch and strike locks	1. 2.5 2. 6	20(Ref.12)	NA	<0.2	4.0E-06
Microtherm	1. Blanketed, unjacketed 2. Blanketed, jacketed w/SS band and latch and strike locks	1. 2.5 2. 6	22(Ref.13)	NA	<0.2	4.0E-06

1

Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments[Note 6] (Cont'd)

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft^3)	Material Density (lb/ft^3)	Characteristic Size	
					μm	Inch
Fiberglass						
Nukon	1. Jacketed with Sure Hold latches 2. Jacketed with standard bands/latches 3. Unjacketed	1. 150[Ref. 29] 2. 10[Ref. 6] 3. 10[Ref. 6]	2.4	159	7.0 fiber diameter	28E-05
Knaupf	Knaupf ET Panel (LDFG similar to Nukon)	10 (Same as Nukon) [Ref. 6]	2.4	159	5.5 fiber diameter	22E-05
Generic	Blanketed with Velcro closures	10 (Same as Nukon & Knaupf[Ref. 27]	3.0 +/- 10%	159	6.75 fiber diameter	27E-05
Knaupf	Fibrous preformed pipe insulation		4.0 +/- 10% or	159	7.5 fiber diameter	30E-05
Owens Corning	Fibrous preformed pipe insulation		3.5 to 5.5	159	8.25 fiber diameter	33E-03
Temp-Mat and Insulbatte	Heavy cloth blanket with stainless steel mesh	17[Ref.6]	11.8[Ref.6]	162[Refs. 9 and 10]	9.0 fiber diameter	36E-05 max. average [Ref.14]
Mineral Wool						
K-Wool	Unjacketed w/wire mesh inner and outer surfaces, heavy cloth blanket with wire hooks at seams	40[Ref.6]	10	90	5 to 7 fiber diameter	20 to 28 E-05

Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments[Note 6] (Cont'd)

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft^3)	Material Density (lb/ft^3)	Characteristic Size	
					µm	Inch
Generic	Generic name for families of products made by Rock Wool Mfg., Roxul, Fibrex, IIG, and others	10[Note 1]	4, 6, 8, 10 pcf are standard	90	5 to 7 fiber diameter	20 to 28 E-05
Other						
Asbestos (Unibestos)	Insulation is blanketed – blankets with Velcro closures or metal band closures	10[Note 2]	7 to 10	153	1 to 8	4 to 32E-05
Koolphen-K	With thin fiber reinforced aluminum antisweat covering w or w/o aluminum jacketing – closed-cell phenolic foam	6	2.2[Ref.30]			
Reflective Metal						
Transco RMI	Reflective metal insulation	190[Ref.6]			See Ref.27 for size distribution	
Darchem DARMET	Reflective metal insulation	190[Ref.6]			Same as Transco	
Diamond Power Mirror	Reflective metal with sure-lock bands and Camlock® strikers and locks	190[Ref.6]			Same as Transco	
Mirror	Reflective metal insulation	4[Ref.6]			Same as Transco	
Fire Barrier Material						
Marinite Board	Dense, heat-treated, inorganic calcium silicate board made of fibers, micro-silica, and binders. High-strength calcium silicate board	64[Note 3]	46 – 65[Ref.32]			

Table 4-1. Damage Characteristics of Common Fibrous Insulation Materials inside PWR Containments[Note 6] (Cont'd)

Insulation Type	Description	Destruction Pressure (psi)	Fabricated Density (lb/ft^3)	Material Density (lb/ft^3)	Characteristic Size	
					µm	Inch
3M Interam	Mat with 3-mil aluminum cover – alumina trihydrate	17[Note 4]	54.3 – 56.8 [Ref.31]			
Kaowool	1. Mat or blanket 2. Mat or blanket with stainless steel mesh to provide reinforcement and enhance for wrapping.	1. 3 2. 5	9.4	160-161[Ref. XX]	2.7 to 3.0 fiber diameter	10.8 to 120 E-05
Silicone foam	Silicone foam/LDSE elastomer	4	~55[Note 5][Ref.34]	~55[Ref.34]		
Gypsum Board	Calcium sulfate dihydrate (gypsum)	10	60[Ref.33]	60[Ref.33]		

Notes:

1. Same material as K-Wool insulation but without wire mesh reinforcement of blanket. From AJIT testing (Test 11-4): even when blanket damaged (torn), most insulation remained in place. Without the wire mesh reinforcement, conservatively assume the same destruction pressure as fiberglass. Destruction pressure may be used for either jacketed or unjacketed fiberglass.
2. Asbestos characteristics are similar to fiberglass except material has greater internal cohesiveness (tensile strength); therefore, AJIT results for fiberglass would be conservative. Fines are smaller (shorter) for asbestos fibers than fiberglass. Destruction pressure may be used for either blanketed and jacketed or unjacketed asbestos.
3. High-strength calcium silicate board. The most applicable tested material is calcium silicate with seam orientation at 180 degrees, except that marinate board has flexure strength approximately 14 times the insulation material. Conservatively assume destruction pressure of 64 psi.
4. Tensile strength: 110 psi; DBA LOCA testing: remains intact and does not dissolve or disintegrate. Dense, flexible ceramic fiber blanket/mat or rigid configuration. Assume strength equivalent to Temp Mat since material is much more dense and has high tensile strength.
5. Assume low destruction pressure. Regardless of size, debris floats.
6. For materials not listed, the manufacturer should be contacted to obtain the type of information listed.

4.2.3 Latent Debris

There are no generic analytical refinements to the method used to quantify latent debris to be described in this section. However, this document does allow for plant-specific improvements to the evaluation of the latent debris source term. If plant-specific conditions justify these refinements, they may be used.

4.2.4 Debris Transport

4.2.4.1 Nodal Network

4.2.4.1.1 Background

In the event of a loss-of-coolant-accident (LOCA) within containment of a pressurized water reactor (PWR), there is the potential for generation of debris with the attendant concern of containment sump screen blockage. The debris, consisting of piping or equipment insulation, protective coatings or paints, concrete dust, or general containment housekeeping materials, may be transported to the containment sump during the recirculation phase of emergency core cooling system (ECCS) and containment spray system (CSS) operations.

The resolution of this issue will potentially require licensees to evaluate containment sump performance with a focus on the generation and transport of debris to the containment sump screens. The methodology presented here provides licensees with one means to analyze post-accident fluid velocities on the containment floor without the complexity and manpower investment required to perform a computational fluid dynamics (CFD) calculation.

4.2.4.1.2 Open Channel Flow Network Analysis Approach

Integral to analysis of debris transport is the determination of fluid velocities from the cooling water sources to the containment sump following the accident scenario. One method of evaluating fluid transport velocities is to develop a CFD model and simulate break and spray flows to determine local velocities. Although the CFD analysis provides an accurate prediction of flow velocities, the manpower requirements to generate the model present an economic basis for pursuing other approaches. An alternative method for predicting flow velocities within containment flooded regions is the development of an open channel network model with the development of boundary conditions based on sources and sinks of cooling water as well as the physical configuration of the containment flooded regions.

Simplistically, the flooded containment floor flow path regions are modeled by open channels; channel flow resistances are calculated based on friction and form losses, sources and sinks of recirculation water are identified and then a network analysis software tool is employed to calculate the individual channel velocities.

To demonstrate the alternative method for predicting flow velocities within containment flooded regions, Westinghouse developed an open channel flow network analysis of the example plant containment floor. Previously the example plant had been modeled with a CFD tool utilizing the same inputs, conditions, and configuration. The results of the model were presented in Reference 37 and a comparison of those results demonstrating reasonable agreement to the channel flow network is provided in Appendix C. The results of the CFD analysis assisted in developing an appreciation of containment channel flow and also served as the benchmark against which the analysis results could be compared. The mapping of the channels onto CFD analysis results is demonstrated in Figure 4-2.

4.2.4.1.3 Open Channel Flow Network Development

Athough the generation of an open channel flow nodal model requires a significant level of effort to develop, the basic understanding of water sources (location and magnitude), flow path definition and constraints, and recirculation water sinks (location and magnitude) and a network analysis tool are the extent of the requirements.

4.2.4.1.3.1 Model Inputs

The prerequisites for successful open channel flow network modeling of the post-accident ECCS sump include the following inputs. The developer must confirm that the inputs are conservative to maximize the calculation of flow velocities. Sensitivities on input parameters will ensure that the assumptions are conservative.

Containment Configuration

Floor plan and elevation configuration – It is essential that the containment flooded region configuration be accurately defined, including any major obstacles to flow (equipment, walls, or architectural features). Basically, an obstacle to flow will be any walls, architectural/structural feature, or major equipment that occupies sufficient space to represent an impediment to flow (additional details provided below). Typically, some or all of the following documents will provide the necessary details:

- General Arrangement Drawings of the Flooded Elevations: Plan, Elevation and Detail views
- Civil or Structural Drawings of the Flooded Elevations: Plan, Elevation and Detail views
- Architectural Drawings of the Flooded Elevations: Plan, Elevation and Detail views

Containment Water Source and Sink Definition

Water sources – The developer must have an accurate knowledge of water sources to the flood plane (basically the same input requirement required to develop a CFD model). The example plant had defined 24 specific sources of post-accident water flowing into the flood plane to be used as the boundary conditions for the modeling. Water sources will likely be comprised of these three major contributors. Additional plant-specific contributions are possible.

Flow sources (magnitudes and direction of point sources to the flood plane):

- Cascaded water from upper floor levels (stairwells, walls, floor drains, etc.).
- Containment spray flow input (sprayed volume if any, wall drainage and inputs to drainage from upper compartment levels).
- Break flow from loop compartment(s).

Conservative maximum flow rates should be assumed to maximize fluid velocities for the assumed accident scenario and debris transport analysis. This data may be extracted from existing containment sump flooding and/or pump NPSH calculations or new calculations of flow delivery to the containment flooded regions will need to be generated.

Water sinks – The developer assumes that the recirculation flow rate passes through the active sump(s). For those plants that have more than one sump, the active sump definition needs to be consistent with the scenario being evaluated. Differences in plant design may dictate multiple sump definitions. The selection needs to be consistent with the defined accident scenario or alternately in the conservative direction to limit the number of scenario cases. Contributors to the sump flow will include scenario-specific ECCS flows and containment spray flow rates or bounding values.

For the example plant, the specification of water sources and sinks have been summarized in Figure 4-1. A similar drawing should be developed for the licensee's plant design.

Channel Definition

Channel boundaries – The developer will define channel segments at essentially any point where there is a significant change in flow area (increase or decrease). At such points, the channel should be terminated and a new one defined until the next structural or flow area change. The same approach is taken at points of significant flow input (or output in the case of the sump) to the network. The open channel specification is based on identifying major flow areas from the various sources to the final destination, i.e., the sump.

The developer will begin the channel definition process at the major point source of water that is farthest from the containment sump(s). The defined channel continues until a significant change in flow area or flow rate occurs. A significant flow area change is considered to be in the range of 15 percent based on the relative magnitude of the impact of additional flow resistance (K for form) and magnitudes of the calculated resistances (f(L/D)) of individual channels for the example plant. Major obstacles that permanently or temporarily divide the flow analysis can result in the generation of parallel path channels in the analysis. Obstacles that cause minor interruption to flow, including structural supports, piping, or smaller equipment such as pumps and valves, can be ignored. These obstacles are acknowledged to cause higher local turbulences but can be assumed to be accommodated within the conservatisms or sensitivities performed.

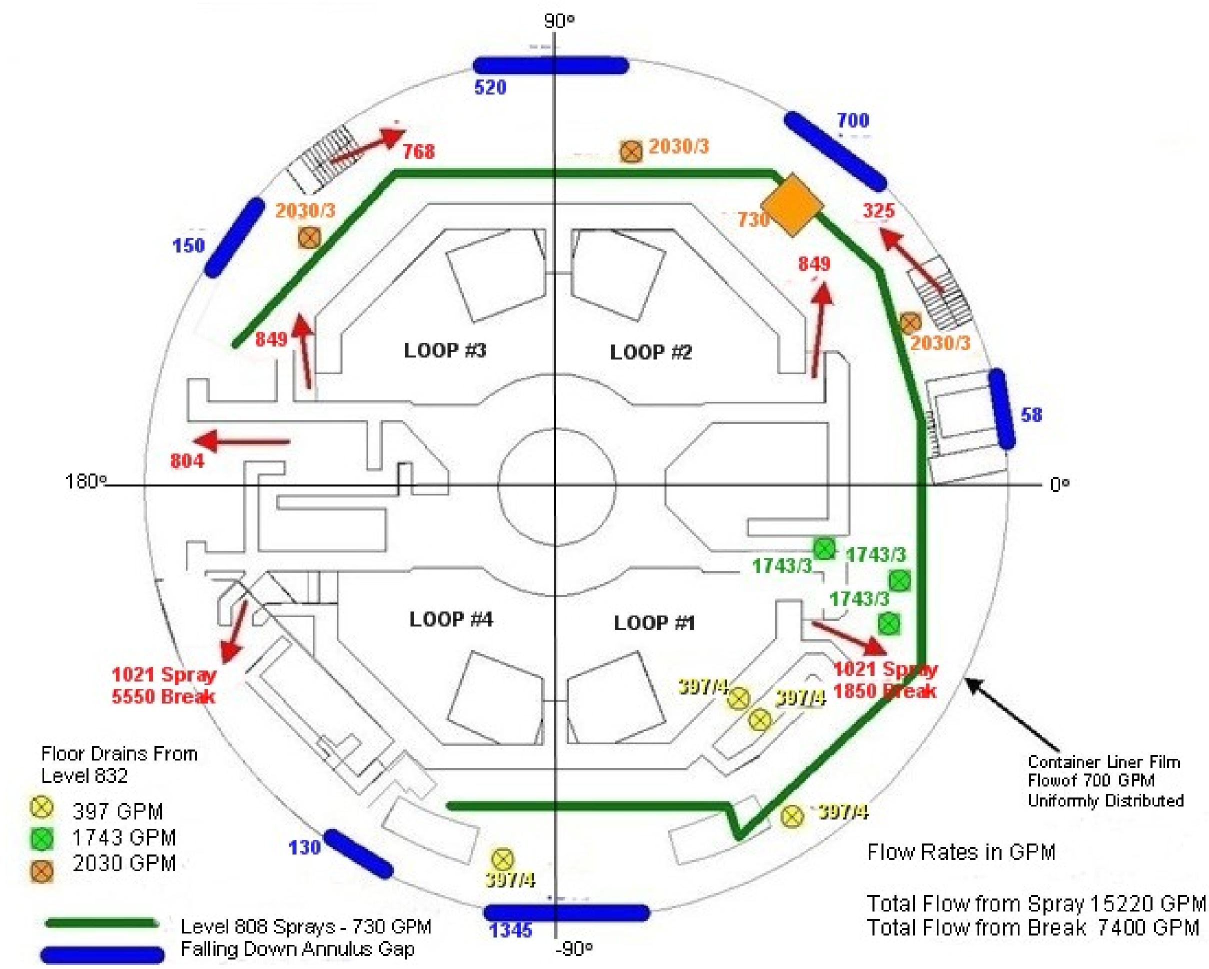


Figure 4-1. Example Plant Water Sources

Portions of the containment floor may not be active in the transport of debris in the steady-state analysis. Once the major channels are defined, the construction of smooth velocity vectors will assist in the definition of major active flow paths, and thereby channel definition or refinement versus reasonably still pool areas. For the most part, dead-end compartments such as loop compartments that are separated from the break, equipment rooms, and passages to these areas as well as regions blocked by architectural features can be considered dead-ended and excluded from the channel flow analysis.

A change in flow rate magnitude of approximately 10 percent is considered significant and will be used to define channel boundaries. Since the channel frictional losses are proportional to the square of the flow, the effect is not a linear function and is therefore more sensitive to flow than changes in friction factors. Plant general arrangement drawings with major equipment documented may be necessary in addition to the structural and architectural drawings identified above.

In the case of the example plant, the containment flood plane is basically a ring of channels around the containment floor with sources defined along the ring header and a destination of the containment sumps. Although most containments are expected to contain a similar contiguous ring from sources to destinations, it is not essential to the modeling. The channel definition is illustrated in Figure 4-2 and superimposed on the water source general arrangement drawing. For illustrative purposes and as a guide in defining channels the above defined channel outlines have also been superimposed on the CFD velocity profile drawing in Figure 4-3. This schematic of channels and velocity profiles should help to provide an appreciation of the above guidelines.

The developer must assume a minimum flooded containment level based on plant calculations maximizing water holdup in flooded compartments as well as any other phenomenon or locations that would minimize level. Minimizing level serves to maximize recirculation flow velocities and the consequential effects including debris transport and debris erosion.

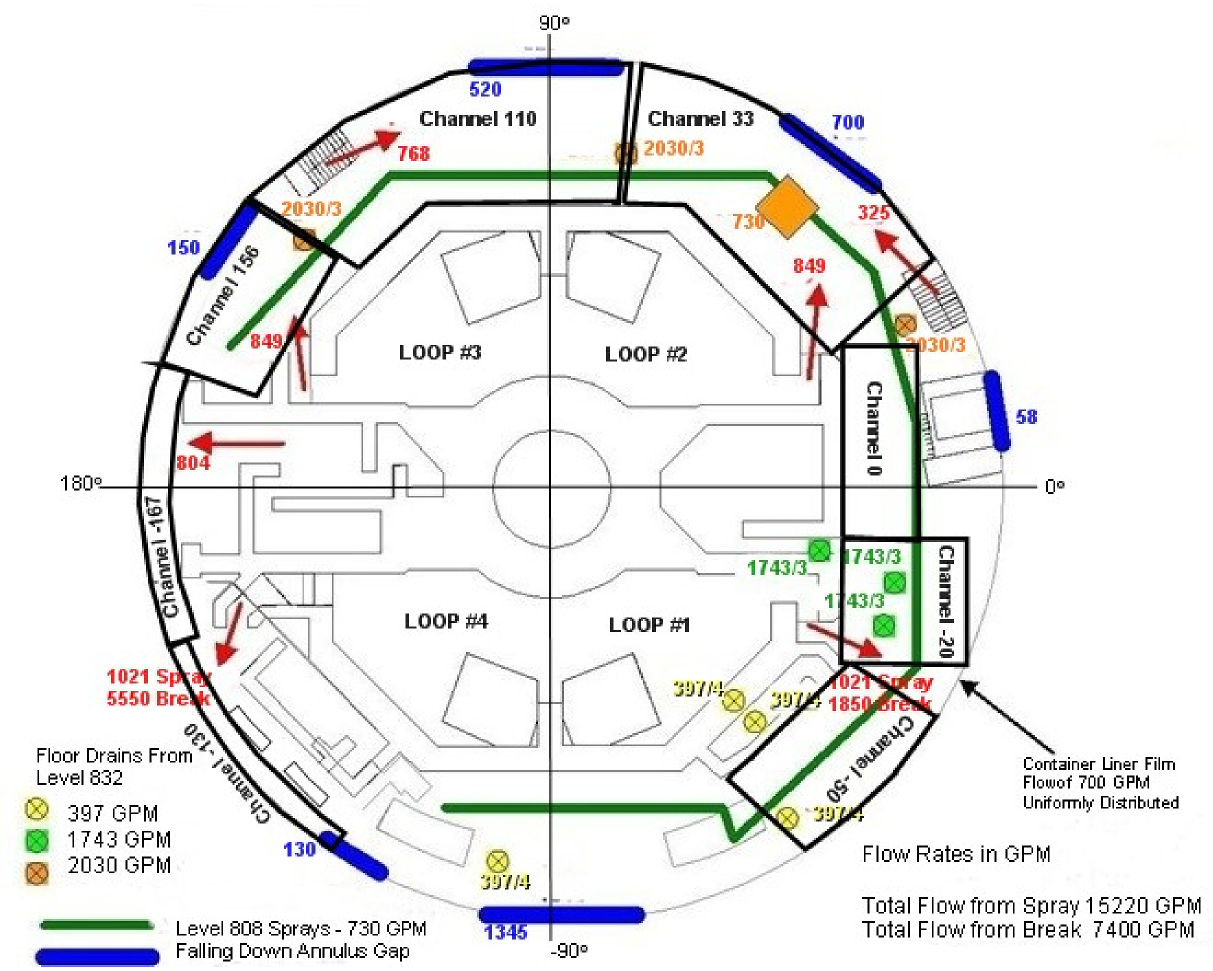


Figure 4-2. Example Plant Network Channel Definition and Water Sources

Channel Loss Calculation

Form and channel frictional losses are to be included in channel resistance to flow. Form losses are primarily based on the reduction or increases in flow areas from channel to channel but may include other changes in velocity head, flow turns, or even obstructions. Open channel flow K factors should be based on data from Crane Technical Paper 410 (Reference 35), Idelchek (Reference 39), Miller (Reference 40), or other accepted sources of loss coefficients.

Open channel frictional losses are calculated based on Altsul's Formula as presented in Reference 36 and then may be verified with the Colebrook-White formula, also from Reference 36.

Altsul's Formula

$$f = 0.1\left[1.46\frac{k_S}{D_H} + \frac{100}{R_e}\right]^{\frac{1}{4}}$$

Colebrook-White Formula

$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left[\frac{k_s}{3.71\,D_H} + \frac{2.51}{R_e\sqrt{f}}\right]$$

where,

f is the Darcy friction factor coefficient
Re is the Reynolds number

$$R_e = \rho\,\frac{V\ x\ D_h}{\mu_e}$$

where,

ρ is fluid density lb/ft^3 (ASME Steam Tables)

V is flow velocity in ft/sec (since Reynolds number is based on velocity, it may be necessary to a assume a value and then iterate the value after the initial model is run)

μ_e is the absolute viscosity in lbm/ft-sec

D_H is the hydraulic diameter of the subject channel and for open flow channels

D_H = 4A/Pw where A is the flow channel area and P_w is the wetted perimeter or base + 2 x height. The base will change with each channel and is included in the summary below.

k_s is the roughness height. From Reference 36. For smooth concrete, a range of values from 0.3 to 3.0 mm is given. Based on the walls being painted with nuclear-grade coatings and often topcoated, the roughness height is expected to be somewhat attenuated and closer to the 0.3 than 3.0 value. If a value of 0.5 mm is used, then

k_s = 0.5 mm(0.00328 ft/mm) = 0.00164 ft

Figure 4-3 provides the resulting network channel definition and includes the calculated friction and form resistances, flow area and hydraulic diameter for each channel for the example plant. Figure 4-4 superimposes the channel network defined on the basis above onto a XY plot of the CFD model results. The CFD plot of velocity profiles providing the basis for Figure 4-4 is a composite of the results presented at the NRC public meeting of March 5, 2003 in Albuquerque, NM (Reference 37).

Channel Definition Refinement

Based on the results of the network nodal analysis, it may be necessary to refine the channel definition and the points at which the flow is introduced into the network. The developer must evaluate the results against assumptions and refine and rerun the analysis as necessary.

4.2.4.1.4 Results

The network nodal mode results for the example plant compare very favorably with the CFD analysis, generally providing an error of less than 10 percent of the total flow. It is recommended that, as a minimum, 10 percent should be added to the calculated flow channel flow calculated rates and sensitivity calculations should be used to identify particular aspects that could significantly influence the results. Finally, in regions with major flow inputs (for example, in this configuration, where the loop compartments empty into channels -130 and -50), turbulence will be created as the flow turns to align with channel flow. For these regions, the calculated velocity must be increased based on the amount of expected turbulence. An examination of the CFD results (Figure 4.2.4.1-2) indicates the effects are fairly localized and, since the channels are defined based on the narrowest cross-section of the region, the bulk effect is expected to be limited in terms of transport. Additional discussion of these factors is provided in Appendix C.

The major discrepancy between the CFD and channel flow results is in the low-flow regime channels. This seems logical since the flow rates are low and the calculated resistances downstream are what actually drive the flow in one direction versus another. The concern that arises is that the debris transported from these areas may experience a limiting obstacle in one direction. This concern is, however, mitigated by the fact that the velocities are sufficiently low in these low-flow regions that the debris that will be transported from these regions will be mostly suspended and not typically susceptible to obstacle holdup. Therefore, it is judged acceptable that these low-flow channels may be calculated to be flowing in the reverse direction. A detailed comparison of channel flow versus CFD analysis is provided in Appendix C.

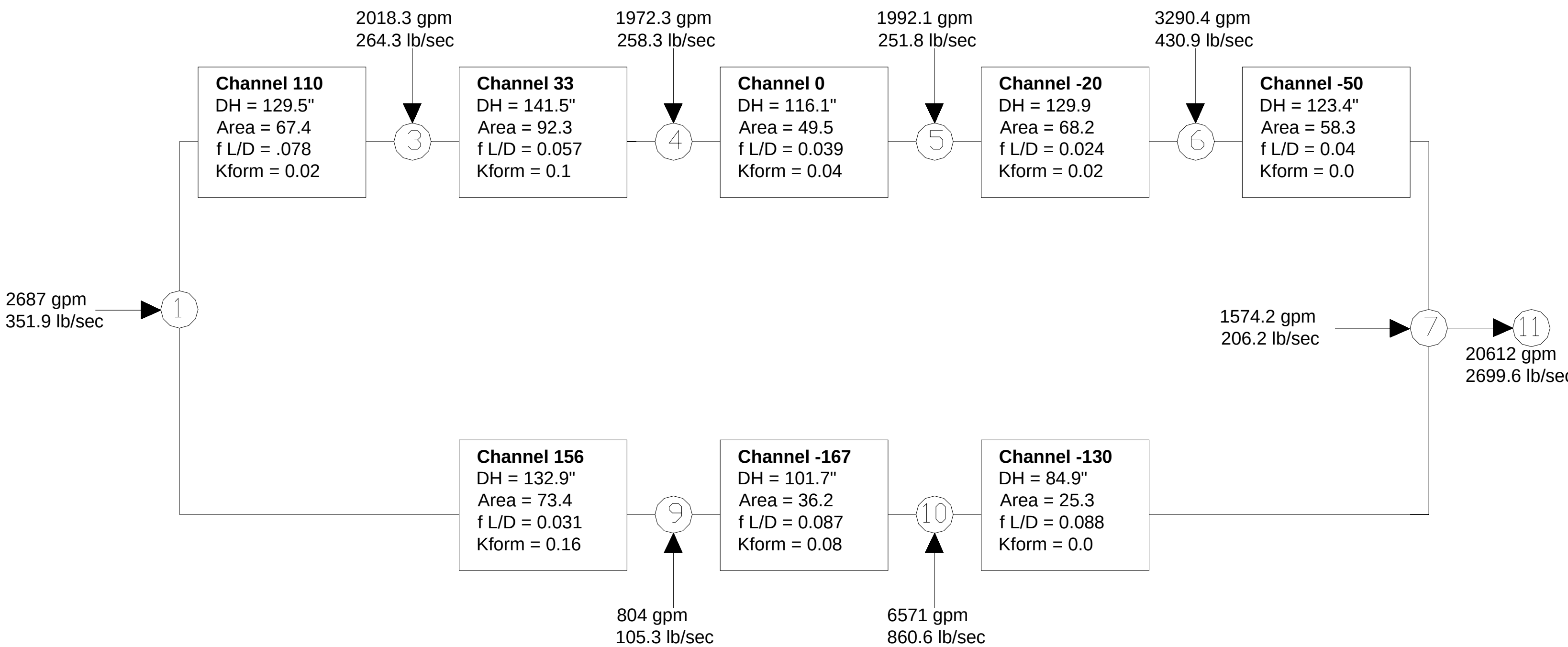


Figure 4-3. Example Plant Network Channel Definition

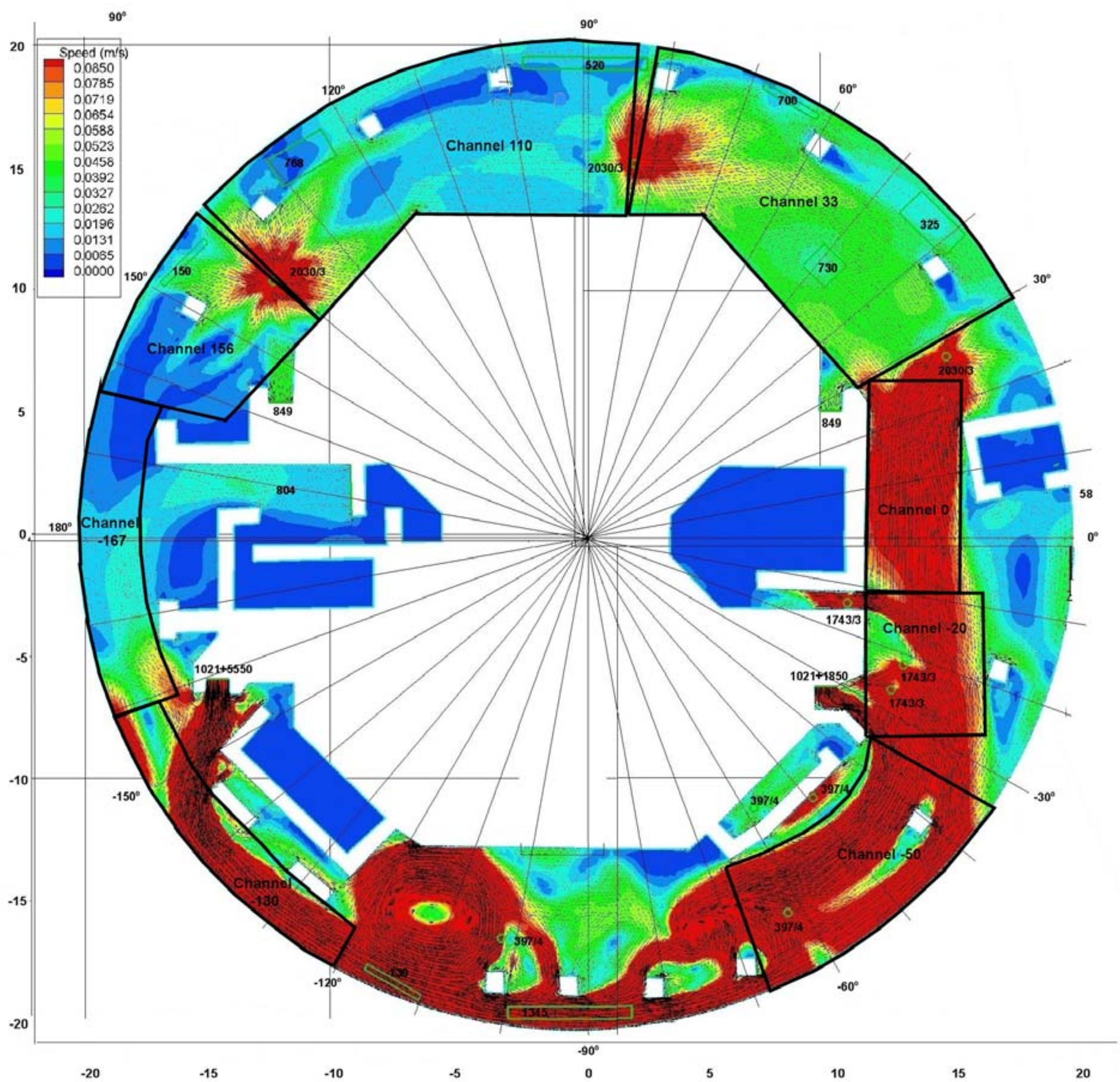


Figure 4-4. Channel Network Superimposed onto yx Plot of the CFD Model Results

4.2.4.2 Three Dimensional Computational Fluid Dyanmics (CFD)

Once the containment recirculation pumps are activated and the ECCS flow is drawn from the recirculation sump, detailed flow patterns in the containment pool can be obtained using state-of-the-art 3D computational fluid dynamics (CFD). The flow is quasi-steady or steady at this stage of the ECCS operation. Several commercially available CFD software applications (FLUENT, FLOW3D) can be used for the flow simulation and analysis, which essentially solve the full set of the conservation of mass and momentum equations (Navier-Stokes equations) as well as turbulence equations for each of the computational elements in the domain of interest. Thus, fully three-dimensional (3D) flow patterns can be obtained, which in turn can be used to predict the various flow paths to the recirculation sump(s), including detailed 3D velocities for the debris transport analysis. The flow velocities and turbulent kinetic energy can be compared to the debris-specific settling velocities, incipient and bulk transport velocities to determine the percentage of debris expected to transport to the sump screen.

The guidance relative to the use of CFD should address:

- Key considerations in defining the containment geometry to be modeled by the CFD code
- Establishment of the water level for these calculations
- Treatment of flow paths to the containment floor
- Treatment of flow paths to and out of the active sump regions
- Treatment of transport restrictions such as curbs and trash racks
- Determination of key transport metrics that include both local velocities (floor transport) and turbulent kinetic energy (debris suspension)
- Comparison of calculated transport metrics to threshold quantities for various debris types, and the resulting determination of overall pool transport fraction for various debris types

The value of performing such detailed transport analyses will depend on several factors including:

- Predominant debris types for a given plant
- Quantity of such debris
- ECCS flow rates

- Containment characteristics that influence velocity and Turbine Kinetic Energy (TKE) profiles in the pool
- Floor pool water level
- NPSH margin versus potential calculated reduction in head loss due to enhanced transport analysis.

Generally it is necessary to provide a qualitative assessment of the benefit to be derived from a CFD analysis to determine the cost-benefit associated with such an undertaking.

4.2.4.2.1 Selection of CFD Software and CAD Package

As a minimum, the CFD software used for performing 3D flow simulations shall have the following features:

- Solves the full set of Navier-Stokes equations
- Turbulence closure options, such the typical k- ε equations with the standard wall function
- Incompressible fluid flow solution
- Modern mesh generator
- Modern preprocessor for specifying fluid property and boundary conditions, such as non-slip walls, inflows, outflows, etc.
- Modern postprocessor or compatibility with independent modern postprocessor for analyzing CFD results

The computer-assisted design (CAD) package used for preparing the 3D geometry of the containment sump shall be capable of performing 3D solid modeling and have a compatible interface with the selected CFD software, i.e., the CAD files shall be imported by the CFD mesh generator.

4.2.4.2.2 Building the CAD Model

The 3D geometric model of the containment pool shall cover the entire volume that forms the pool after a LOCA, i.e., all the open space from the containment floor (and the containment sump floor) to the potential maximum water level, including a short length (at least five diameters) of the suction pipes from the recirculation sump(s). A detailed review of the containment civil and mechanical pipe drawings, and any available photographs, shall be made to identify major flow obstructions, such as structures, equipment, pipes, etc. that will be submerged in the pool. Obstructions less than 6 inches in diameter or the equivalent may be omitted.

If available, use an existing electronic 3D solid model (file) of the containment as a basis for the geometric model. If a CAD file is unavailable or is not used, the containment geometry and details of obstructions shall be obtained from as built drawings and/or a containment walkdown.

4.2.4.2.3 Building the CFD Model

Computational Mesh Generation

The 3D geometric CAD model is imported into the mesh generator. The geometric model needs to simulate the actual pool water level and break location, thus requiring separate meshes for each of the LOCA break locations and water levels to be analyzed. For better accuracy of the CFD solution, meshes shall be clustered around the break inflow, sump intake(s), and other areas of interest where high velocities and gradients are expected. Hexagonal meshes shall be used as much as possible. Computational meshes shall be of good quality, i.e., the "skew angle" shall be less than 0.85.

Specification of Material Properties and Boundary Conditions

The computational meshes are read into the selected CFD package and preprocessing of the CFD model is performed. Preprocessing includes the following:

- Specify the properties of water in the containment pool.
- Specify boundary conditions. The types of boundary conditions associated with the containment pool flow simulations are "non-slip" walls for solid surfaces, a zero-stress lid for the water surface, inflows for the break and core spray flow and outflows for the suction pipes of the recirculation sump(s). It may be conservative to assume that the break flow falls freely by gravity onto the water surface from the break location without interruption by any structures. Knowledge of plant-specific spray flow path(s) shall be obtained to determine the proper location(s) and method for introducing spray flow into the pool. The water surface may be treated either as a zero-stress rigid lid or a free surface, depending on the capability of the CFD software used. Outflow or pressure is generally specified at the recirculation sump suction pipe outlet.
- Specify the accuracy of discretization schemes. Generally, a second-order accuracy for discretization schemes shall be used in the CFD analyses.

4.2.4.2.4 CFD Analysis

A converged CFD solution shall be obtained by running the CFD model for a sufficient time. If the velocity components, turbulent kinetic energy and turbulent energy dissipation rate do not change appreciably with subsequent iterations, it is an indication that a converged solution has been achieved. The generally acceptable convergence criterion is that the residuals of these pertinent flow parameters should be less than 10. Other equivalent criteria may be used if properly justified.

4.2.4.2.5 CFD Results for Debris Transport

The CFD results shall be post-processed to produce meaningful plots that assist in debris transport analysis. Types of useful plots are as follows:

- For a given type and size of debris, plot velocity magnitude contours for the minimum bulk transport velocity (from available experimental data, see Table-4-1) at a selected elevation(s) within the containment pool using the CFD software's built-in post-processor or an independent post-processor. Conservative results are obtained if the elevation selected for analysis gives the maximum area under the bulk velocity contour. The area within the velocity magnitude contour connected to the recirculation sump is determined, and it may be conservatively assumed that debris in this area (of the given type and size being analyzed) will be transported to the sump screen. Refinements based on the flow pattern may be incorporated.

- The effects of turbulence level may be taken into account by assessing whether debris particles or fibers will stay suspended due to the instantaneous vertical velocity component being equal to or greater than the settling velocity of the debris particles. The maximum instantaneous vertical velocity is calculated by adding the fluctuating vertical velocity to the (CFD) computed mean (time average) vertical velocity. The fluctuating velocity is determined from the computed turbulent kinetic energy, k. Contours within which the instantaneous vertical velocity component is equal to or greater than the settling velocities of different type and size of debris being analyzed may be used to assess if this debris may become or stay suspended.

- Velocity vectors and flow streamlines may also be used to assist the analysis of debris transport.

4.2.4.2.6 Example of a CFD Simulation

Assumptions

An example PWR containment is shown in Figure 4-1. The flow patterns are calculated with FLUENT software. The containment has a diameter of about 100 feet and has structures in the pool as shown. There are two recirculation pumps with suction pipes of 1-foot diameter. It is assumed that spray flow enters the water surface from a 6-inch annular gap on the outsider perimeter and two rectangular stair wells (shown in solid color). It is assumed that the break jet (shown as a small circle of solid color) has a diameter of 10 inches when it free-falls from its break location. Flow conditions being simulated are as follows:

- Water depth: 3.5 feet

- Break flow: 2,000 gpm
- Containment spray flow: 1,000 gpm (60 percent of the spray flow is assumed to enter into the water surface from the annular gap)
- Two recirculation pumps are in operation with 1,500 gpm each
- Fluid medium is water

Model Setup

A total of 1.2 million hexagonal computational meshes were generated as shown in Figure 4-1. It can be seen that meshes are clustered around the LOCA break, spray flow inlets (the annular gap and two stairwells), recirculation pump intake and the structures.

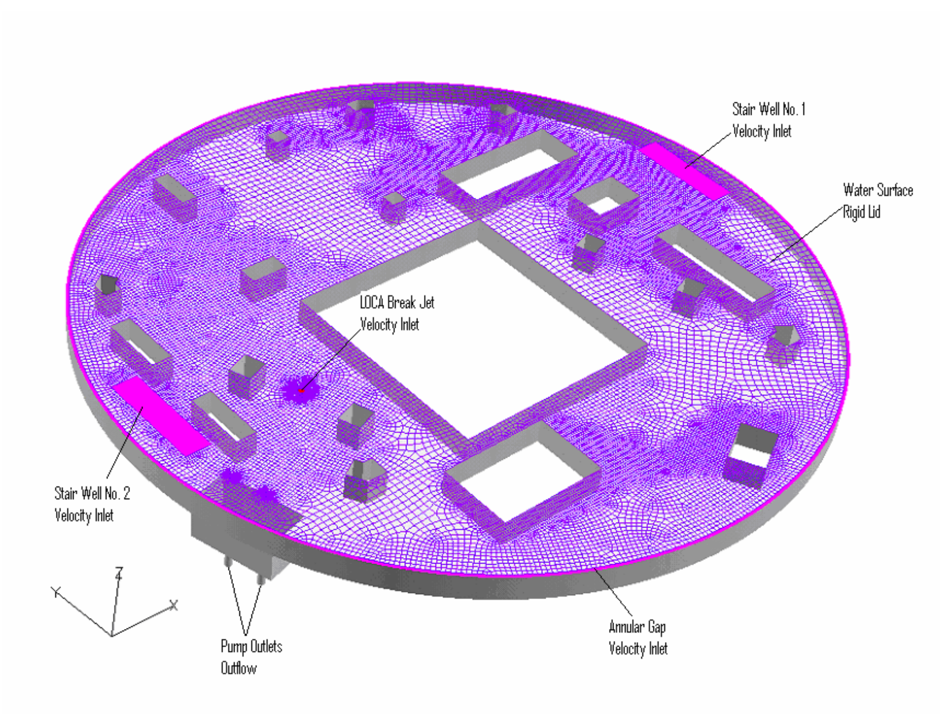


Figure 4-5. Containment Geometry and Computational Meshes

CFD Calculation Results

Figure 4-2 plots streamlines of the flow field that illustrates the general flow patterns in the containment. These streamlines are colored by velocity magnitudes. Figure 4-3 shows two velocity magnitude contours (0.25 ft/sec in blue and 0.5 ft/sec in red). These contours are used to calculate the areas in which the debris with the corresponding bulk transport velocities are assumed to be transported to the sump screens.

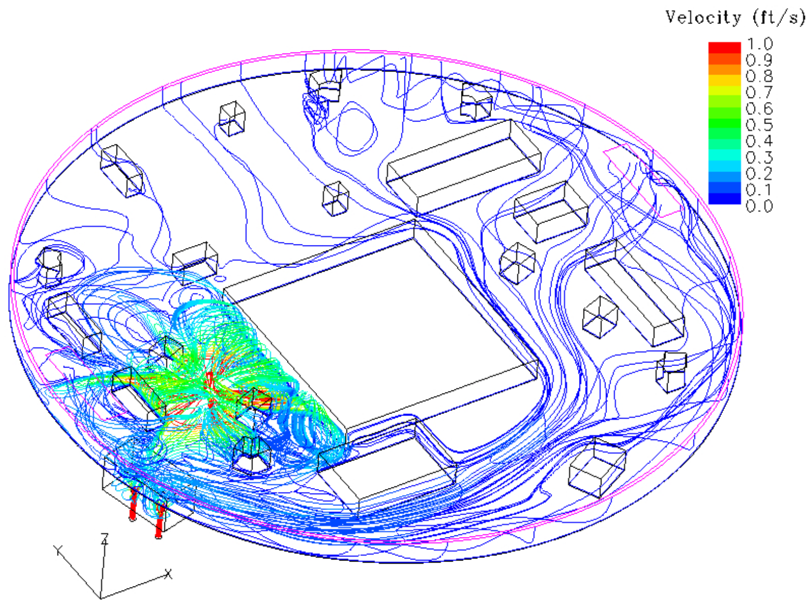


Figure 4-6. Streamlines Illustrating Flow Patterns

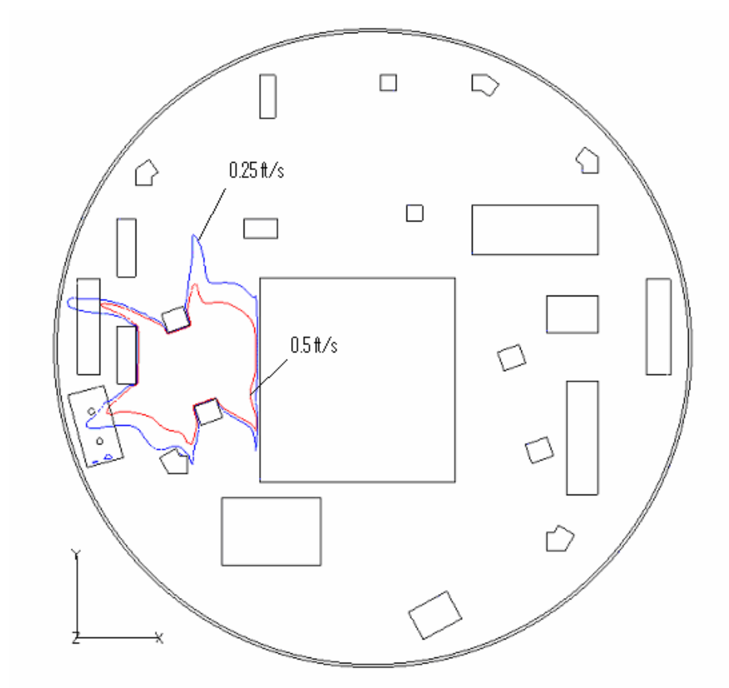


Figure 4-7. Velocity Magnitude Contours near the Containment Floor

Table 4-2. Debris Transport Reference Table

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
A. Fibrous Insulation								
1. Fiberglass – Generic								
2. Fiberglass – Nukon	a. 6" b. 4" c. 1" d. 1/4"x 1/4" clumps e. loose fibers	a. 2.4 b. 2.4 c. 2.4 d. 2.4 e. 175	a. 0.41 b. 0.40 c. 0.15 d. 0.175 e. 0.008	a. 0.084 b. 0.080 c. 0.011 d. 0.14 e. 3E-05	a. 0.12 b. 0.12 c. 0.12 d. 0.16 e. NA	a. 0.25 (2" curb) 0.34 (6" curb) b. 0.25 (2" curb) 0.34 (6" curb) c. 0.25 (2" curb) 0.34 (6" curb) d. ? e. NA	Min. TKE to suspend calculated from settling velocity for sizes a, b, c, and e	a. NUREG/CR-6772 b. NUREG/CR-6772 c. NUREG/CR-6772 d. NUREG/CR-6369, NUREG/CR-6808 e. NUREG 6808
3. Fiberglass – High Density					0.2 (shreds) 0.3 (4 x 4 x 1 in. and 4 x 1 x 1 in.) 0.9 (whole pillow)			NUREG-0897, Rev. 1
4. Fiberglass – Temp-Mat		11.3 macro	See comment.		See comment.	See comment.	No data specifically for Temp-Mat. Conservatively use data for NUKON (NUKON has a lighter macroscopic density).	NUREG-6808, Section 3.2.1.2

1

Table 4-2. Debris Transport Reference Table (Cont'd)

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
5. Fiberglass – Transco (Thermal Wrap®) a. Shredded b. 4-in. x 6-in. pieces			a. 0.13 b. Not Tested		a. 0.07 b. 0.12	a. 0.22 (2-in. curb) b. 0.25 (6-in. curb)	Most limiting transport velocities were taken from NUREG/CR-6772. Transco tested various sizes of debris for transport velocities. Submersion of floating samples occurs within seconds for high temperatures (~90°C). Settling velocity weakly dependent on temperature (higher velocities for higher temps)	a. NUREG/CR-6772 b. NUREG/CR-6772
6. Mineral Wool a. 4-in. x 4-in. x 1-in. b. Shreds					a. 0.4 b. 0.3		Mineral Wool floats unless forced to sink.	NUREG/CR-2982 and NUREG-0897
7. Miscellaneous Fibrous a. Asbestos b. Unibestos								

Table 4-2. Debris Transport Reference Table (Cont'd)

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
B. Calcium Silicate Insulation								
Generic - Chunks with dust + fibers			Not tested: see comment on dissolution		0.10 (dust + fibers) 0.25 (small chunks) 0.30 (larger chunks)	Not tested: see comment on dissolution	Tests performed at ~20°C. Chunks were almost fully dissolved after immersion in near-boiling water for 20 min. 10-g pieces lost 50 to 75% of weight after immersion in 80°C water for 20 min.	NUREG/CR-6772
C. Reflective Metallic Insulation								
1. Stainless Steel	a. 1/2" square crumpled foils b. 2" square crumpled foils c. half cassette d. cover		a. 0.37 b. 0.48	a. 0.068 b. 0.115	a. 0.28 b. 0.28 c. 1.0 d. 0.7	a. 0.84 b. 0.84 (2" curb)	Min. TKE to suspend calculated from settling velocity	a. NUREG/CR-6772 b. NUREG/CR-6772 c. NUREG/CR-3616 d. NUREG/CR-3616

Table 4-2. Debris Transport Reference Table (Cont'd)

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
2. Aluminum	Mix of flat, crumpled, & semi-crumpled foils up to 2" square		0.11	0.0061	0.20		Min. TKE to suspend calculated from settling velocity	NUREG/CR-6772
D. Fire Barrier								
1. 3M Interam								
2. Fiberglass blanket			Same as Nukon		Same as Nukon	Same as Nukon	Since no data for "generic fiberglass" is available, it is recommended that the data for Nukon be used to represent low-density fiberglass.	
3. Kaowool a. Shredded b. 4-in. x 6-in.			a. 0.21 b. Use value from (a) above		a. 0.09 b. 0.12	a. 0.25 b. 0.25 (2-in. or 6-in. curb for both debris types)	Based on similarity of other hydraulic transport characteristics, suggest using same settling velocity for shredded and cut Kaowool.	NUREG/CR-6772

Table 4-2. Debris Transport Reference Table (Cont'd)

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
4. Marinite board a. 1-in. x 1-in. b. 4-in. x 4-in. Three values for density: Marinite-23 =23 lb/ft^3 Marinite-36 =36 lb/ft^3 Marinite-65 =65 lb/ft^3			a. 0.59 - 0.63 b. 0.42 - 0.60		a. 0.77 b. 0.77	a. Not tested b. Not tested		NUREG/CR-6772
5. Silicone foam			--		--	--	Floats – Readily transports at any velocity	NUREG/CR-6772
E. Other								
1. Koolphen (closed cell phenolic)								
2. Min-K (microporous)								
3. Lead Wool Macroscopic Density = 10-15 lb/ft^3								
4. Dirt/Dust	10 µ particulate	156						

Table 4-2. Debris Transport Reference Table (Cont'd)

Debris Category/Type	Size	Density (lbm/ft^3)	Terminal Settling Velocity (ft/sec)	Minimum TKE Required to Suspend (ft^2/sec^2)	Flow Velocity Associated with Incipient Tumbling (ft/sec)	Lift-Over-Curb Velocity (ft/sec)	Comment	Reference(s)
5. Sludge (Iron)	Particulate	324	N/A		N/A	N/A	No credible source of iron sludge identified for PWR's	
F. Coatings								
1. Epoxy	15-mil thick chips	94	0.15	0.0113	0.4	0.5 (2-in. curb)	Min. TKE to suspend calculated from settling velocity	NUREG/CR-6772
2. Alkyd	10 µ particulate	98	2.25E-04	2.53E-08	NA	NA	Settling velocity calculated per Stokes' Law Min. TKE to suspend calculated from settling velocity	
3. Inorganic Zinc	10 µ particulate		6.74E-04	2.27E-07	NA	NA	Settling velocity calculated per Stokes' Law Min. TKE to suspend calculated from settling velocity	

4.2.5 Head Loss

4.2.5.1 Thin-Bed Effects

No refinements are offered for the evaluation of this bed effects beyond those given in Section 3.7.2.3.2.3.

4.2.5.2 Alternative Methods for Head Loss Calculations

Although there are no analytical refinements recommended for the head loss correlation for flat screens (the NUREG/CR-6224 correlation), this section presents information that may be helpful in refining the head loss analysis as a whole or useful in the development of correlations for alternate strainer designs. The following information is presented in this section:

- Background information on the development of head loss correlations
- A summary of head loss tests performed to date
- The currently available head loss correlations
- Discussion of possible analytical refinements
- Discussion of head loss correlations for alternate strainer designs

Background

The head loss across a screen is highly dependent on the size and shape of the insulation debris reaching the screen. These debris characteristics depend on a variety of factors, including the type and manufacturer of the material (e.g., Nukon versus mineral wool versus Thermal-Wrap); plant aging effects such as the duration of exposure to high temperatures; the mode of transport (blowdown or washdown) to the recirculation pool; and the recirculation pool agitation at the time of the materials transport (e.g., chugging or falling water). For example, fiber debris may vary in size from individual fibers, typically a few millimeters in length, to shreds or small pieces that retain some of the original structure of the insulation blankets.

Nearly all of the suspended fibrous and metallic insulation debris approaching the strainer will be trapped by the strainer, except for a small quantity of finely destroyed debris (e.g., small individual fibers) that may pass through the strainer during the early stages of bed formation. During these early stages, the debris beds would be very thin and have a nonuniform thickness. In extreme cases, the debris bed may result in a partially covered strainer with open voids until more debris materials are transported. Initially, such beds may not possess the required structure or strength to filter the particulate debris, especially particulates that are a few microns in size. As a result, the majority of the particulate debris approaching the strainer during these early stages will most likely penetrate the strainer and circulate through the reactor core region. The concerns arising from this consideration are known as “downstream effects” and are addressed in Section 7.3.

The non-uniformity of the bed during its initial formation may result in a redistribution of incoming flow, with more flow through the open areas where the flow resistance is lower. As a result of this redistribution, the newly arriving debris will be carried to the open areas of the strainer where they would be deposited. With time, continuous addition of debris in this manner will ultimately lead to formation of a thin, uniform debris bed on the strainer surface.

Some PWRs have quiescent pools (i.e., low-turbulence pools) and low approach velocities so that some or all of the material may not be transported to the screens. The material (particularly paint and RMI) that is transported near the floor may tend to accumulate near the front of the vertical or inclined screens. These factors should be considered in the development of the actual debris loads to which the screen will be subjected.

As the debris bed thickness increases, it acquires the required structure to commence filtering particulate debris passing through it. Filtration efficiencies close to 100 percent may be possible for larger particulates such as paint chips and concrete dust, but efficiencies on the order of 25 to 50 percent have been reported for filtration of particles ranging in size from 1-10 µm. As such, the quantity of particulate debris filtered by the fiber bed and, consequently, the head loss across the strainer (which is an increasing function of both the amount of debris trapped on the strainer and its geometry) are strong functions of the size distribution of the particulate debris reaching the strainer. This also brings into focus the important role played by filtration efficiency in estimating the head loss.

The head loss incurred during the debris bed buildup and the time at which such head loss may exceed the available NPSH margin are important factors in design considerations and in planning for mitigating actions. The rate and magnitude of head loss increase and will be influenced by the following factors:

- Amounts of various types of debris reaching the strainer and their rate of transport at any given time.
- Size distribution and type of debris reaching the strainer.
- Filtration efficiency of the fibrous bed to trap particulate matter.
- ECCS flow rate and approach velocity.
- Recirculation pool temperature.
- Plant-specific considerations such as screen/strainer area, hole or mesh size, design, arrangement and flood height.

The detail to which such phenomena are modeled can significantly affect the calculated head loss at any given time. Experience has shown the need to adopt a plant-specific transient analysis model that incorporates all these considerations for performance evaluations. Moreover, mixtures of fibrous materials and microporous insulation or calcium silicate may exhibit significantly high head loss for relatively low amounts of fibrous material. Consequently, it is not appropriate to extrapolate head loss obtained for one mixture of debris to another without taking into account the debris characteristics. Any predictive calculations should be based on test data that provide accurate debris characteristics of the constituents of the debris beds. Extrapolation of correlations that do not factor the debris characteristics explicitly should not be practiced.

4.2.5.2.1 Summary of Significant Head Loss Tests

Table E-2 in Appendix E provides a compilation of the testing and data, results, and pressure drop relationships developed by several organizations that have issued publicly available head loss test information. In addition, Table E-2 provides a summary of experiments and tests. The insulating materials used or simulated in these experiments consisted of:

- Mineral wool (rockwool)
- Low-density fiberglass (Nukon, Transco Thermal-Wrap)
- High-density fiberglass
- Caposil (Unibestos) (calcium silicate containing asbestos fibers)
- Calcium silicate (diatomaceous earth, “Newtherm,” “Calosil”)
- Insulation particulates (e.g., calcium silicate and alumina)
- Reflective metallic insulation with stainless steel foils
- Reflective metallic insulation with aluminum foils
- Microporous insulation, including Min-K and Microtherm

Other debris materials included in some tests were:

- Paint chips
- Rust (iron oxide corrosion products)
- Metallic particulates

Early Tests

Various techniques were used to generate insulation debris of representative sizes. For fibrous insulation, these included manual (hand) shredding, mechanical shredding (meat mincer, leaf shredder) and jet fragmentation (steamjets, waterjets, and airjets). The actual size class of the fibrous debris varied from as-fabricated blankets (without covers or scrims) to finely destroyed debris consisting of a significant quantity of individual fibers. Production techniques such as manual shearing and jet fragmentation were used for generation of nonfibrous insulation fragments used in the experiments (e.g., metallic insulation).

U.S. boiling water reactor (BWR) corrosion products were initially simulated using iron oxide particles that are larger than 75 mm owing to the lack of information related to size characteristics of the rust particles usually found in the BWR suppression pools. The U.S. BWR Owners’ Group (BWROG) later provided the information in Table 4-1 that was used to size the corrosion products.

Table 4-3. Size Distribution of Suppression Pool Sludge

Size, mm	% by weight
0-5	81
5-10	14
10-75	5

The paint chips varied from 0.125 to 0.25 inches in size; and from 0.02 to 0.16 grams in weight. The size of the paint chips used in the experiments was based on engineering analyses provided by the BWROG for BWR containment coatings.

The head loss experiments listed in Table 4.2.5.2-2 can be broadly categorized as 1) separate effects experiments, and 2) small-scale strainer qualification tests. The focus of the separate effects tests was to develop relationships that correlate strainer head loss to flow velocity and the amount of debris on the strainer. The intent of the investigators was to use these relationships, together with engineering judgment and assumptions regarding the debris generation and transport, to provide the basis for design and sizing of the strainers. Typically, these tests employed a flat-plate strainer and a closed test loop to conduct experiments. Note that the results from a once-through column and closed-loop and open-loop recirculating experiments can produce significantly different results if these experiments are not preplanned to separate such effects.

Typical data reported by the closed-loop experiments included head loss as a function of strainer approach velocity and the quantity and type of debris added to the test loop. Some of the European experimental data were reported in the form of coverage (kg/m^2) of insulation material required to produce a head loss of 2 meters of water across the strainer as a function of velocity. The material in Table 4.2.5.2-2 includes the parameters and range studied in each experiment. The head loss data were reported for theoretical bed thicknesses in the range of 3 mm to about 25 cm; approach velocities in the range of 1 to 0.5 m/sec; at temperatures of 20°-25°C and 50°-55°C; and for nominal sludge-to-fiber mass ratios in the range of 0 to 60. Considerable scatter exists in head loss data from different sources. Careful examination of the experimental data suggests that scattering can be attributed to the following:

- Variation in size classes of debris used in the experiments to simulate LOCA-generated debris. (Typically, debris produced by manual methods is larger, that is, NUREG/CR-6224 Classes 6 and 7, and resulted in lower pressure drops. On the other hand, debris produced by mechanical methods and jet fragmentation was much smaller and resulted in higher pressure drops. Further discussions related to the effect of size class on the head loss across the strainer are presented in previous sections.)

- Variation in the age of the fibrous insulation debris.

- Differences in experimental test loops.

- Differences in the range of experimental parameters. (For example, European experiments were conducted at very low velocities, 1-10 cm/s, while the U.S. experiments were conducted at much higher velocities, 5-50 cm/s.)

- The chosen method of correlating the data. (In most cases, purely empirical relationships were sought to correlate the head loss data that were obtained for a limited range of experimental parameters. This seriously limited extendibility of these individual correlations beyond their original range of study.)

Testing Performed After ~1995

More recent tests and experiments were performed by different organizations either to provide a basis for design of ECCS recirculation strainers and screens or a basis for regulation. The organizations recognized the major shortcomings and limitations in the early testing programs and devised the more recent ones to provide sufficiently detailed and proven information for the intended purposes. Documents such as NUREG-6224 and the BWROG Utility Resolution Guide (URG) are based on and/or refer to these recent investigations. Following are some of the functional areas investigated:

- Head loss characteristics of various types of fibrous insulation by itself and in combination with particulate matter (sludge).

- Head loss characteristics of other less common materials, such as containment coatings, microporous insulation debris (Min-K and calcium silicate), in combination with fibrous insulation debris.

- Head loss characteristics of reflective metallic insulation debris, by itself and in combination with other debris such as fibrous and particulate matter.

- Head loss characteristics of insulation debris deposited on specific strainer or sump designs.

Some of the previous difficulty in obtaining repeatable and comparable results lay in the testing methodology. Having results that can be directly correlated with the realistic plant configurations and arrangements, or that can be properly scaled to these, is important.

4.2.5.2.2 Head Loss Correlations

Several different approaches and methodologies have been employed for predicting head loss across debris beds. These approaches include theoretical or semi-theoretical relationships and empirical relationships. As discussed below, some of the early empirical relationships, while adequate for their intended purpose of predicting pressure drop across a single media debris bed, are inadequate for predicting pressure drop across mixed debris beds. This inadequacy may have contributed to some of the events challenging ECCS recirculation capability. It is important to anticipate what debris may be transported to an ECCS screen, and to employ head loss correlations valid for the combination of materials, anticipated debris characteristics, and conditions expected. Different forms and approaches for head loss correlations are described in the following paragraphs.

Empirical Correlation for Fiber-Only Beds

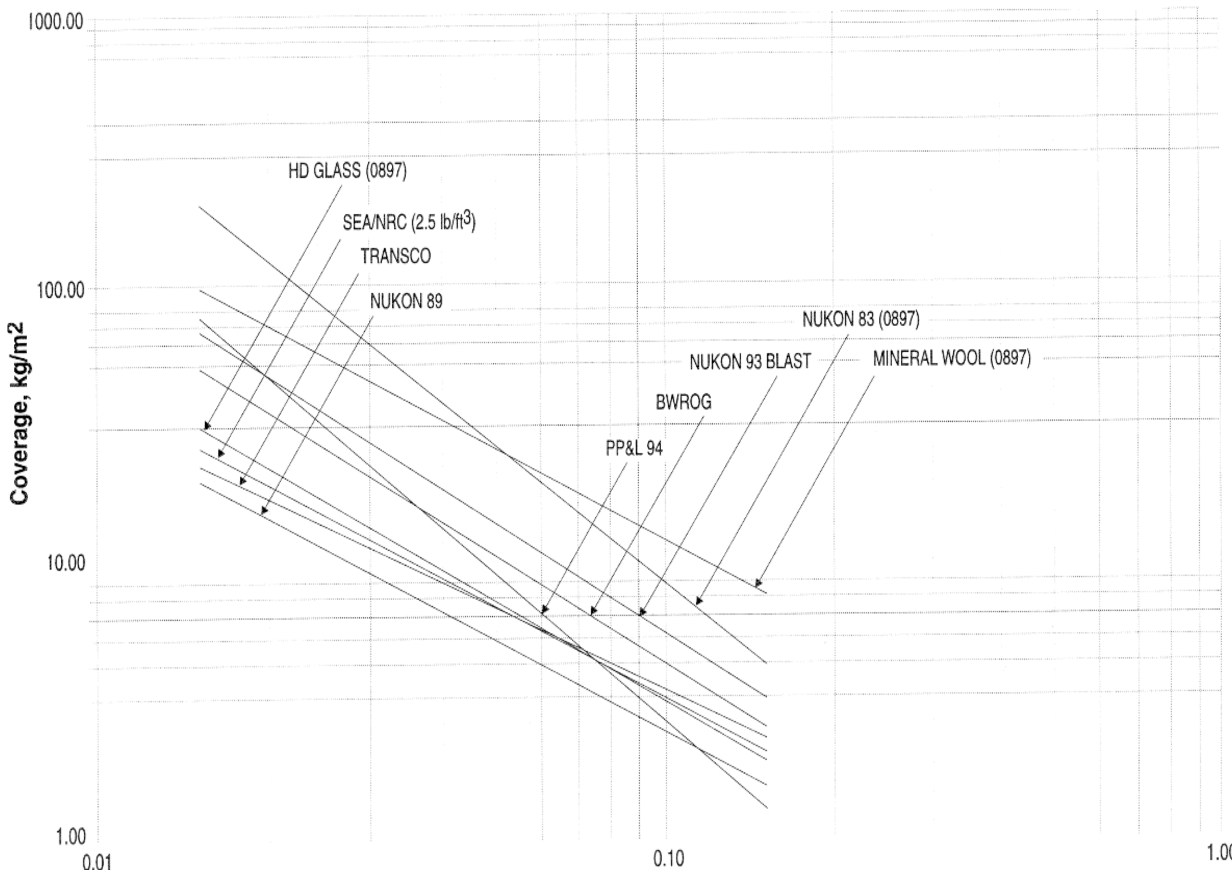
Early strainer or screen design methods typically assumed that the screen/strainer pressure drop was primarily due to an accumulation of fibrous debris. For pure fiber beds, most studies developed empirical relationships to relate velocity and bed theoretical thickness or fibrous debris accumulation to strainer pressure drop. The relationships were usually of the following form:

$$\Delta H = aV^b e^c \tag{1}$$

where

ΔH	is strainer head loss (ft)
V	is strainer approach velocity (ft/sec)
e	is debris bed theoretical thickness (ft)
a, b, and c	are empirical constants determined in experiments

These relationships, together with engineering judgment and assumptions regarding the debris generation, debris characteristics, and transport, provided the basis for design and sizing of the strainers. Some attempts were also made to employ similar relationships to correlate experimental data obtained for mixed beds. The various correlations developed for debris beds formed of pure mineral wool beds, pure low-density fiberglass beds, and mixed beds formed of fiber and sludge mixtures are contained in the summary material of Table 4.2.5.2-2. The predictions of the correlations for low-density fiberglass are illustrated in Figure 4.2.5.2-1, which clearly illustrates the variabilities and uncertainties associated with early correlations that apply only to the low-density fiberglass tested. Other insulation materials may exhibit different head loss characteristics.



Velocity, M/sec

Figure 4-8. Comparison of Available Head Loss Correlation for Low-Density Fiberglass Material Plotted as Strainer Coverage Required to Develop 2 Meters Water ∆P for Various Fibrous Materials

U.S. NRC NUREG/CR-6224 Head Loss Model

To minimize some of the shortcomings previously listed, the U.S. NRC sought a semi-theoretical approach for correlating the experimental data. Equation 2 is of a form containing two terms that account for head loss in the laminar and turbulent flow regimes, derived from the Kozeny-Carman and Ergun Equations as explained in Table 4.2.5.2-2.

$$\frac{\Delta P}{t} = 3.55\, S_v^2 (1-\varepsilon)^{1.5} \left[1 + 57(1-\varepsilon)^3\right] \mu V + \frac{0.66\, S_v\, (1-\varepsilon)}{\varepsilon} \rho V^2 \qquad (2)$$

where,

ΔP	is the pressure drop that is due to flow across the bed (dynes/cm^2)
t	is the height or thickness of the fibrous bed (cm)
μ	is the fluid dynamic viscosity (poise)
ρ	is the fluid density (g/cc)
V	is the fluid velocity (cm/sec)
ε	is the bed porosity
S_v	is the specific surface area (cm^2/cm^3)

This correlation has the following salient features:

- Head loss dependence on the type of fibrous insulation material (e.g., mineral wool versus low-density fiberglass) can be handled directly by varying material properties (fiber-specific surface area, fiber strand density, and material packing density) in the equation. This eliminates the need for developing a separate equation for each debris type.

- Head loss dependence on particulate can be handled directly by varying the bed porosity.

- The same equation is valid for laminar, transitional, and turbulent flow regimes, which maximizes its usage in the plant analysis.

- Head loss dependence on water temperature can be handled explicitly through the use of flow viscosity in the equation.

- Compressibility effects can be handled by analysis.

A series of experiments was conducted by the U.S. NRC to obtain head loss data that can be used to validate the correlation previously listed. The experimental data obtained from these tests formed the most comprehensive head loss database for debris beds formed of Nukon and corrosion products, encompassing an experimental parameter range of 3 mm to 10.2 cm for thickness; 5 to 50 cm/sec for approach velocity; 0 to 60 for sludge-to-fiber mass ratios; and at temperatures of 24° and 52°C. Detailed comparison of the correlation predictions with these experimental data is presented in NUREG/CR-6224. This correlation was used for the plant evaluation reported in NUREG/CR-6224 and has also been incorporated into the BLOCKAGE computer code developed by the U.S. NRC.

The following limitations of this correlation are identified for the potential user:

- The correlation may not be applicable for nonuniform debris beds since the correlation is developed based on the assumption that the debris forms a uniform bed. This may limit equation applicability to very thin beds or thin beds formed on specialized strainers.
- The correlation may not be applicable to thin fiber beds coupled with high sludge-to-fiber mass ratios since nonuniform debris bed thicknesses, including open spaces, were observed in the ARL experiments.
- Although this correlation is expected to provide an upper-bound estimate for the head loss, these limitations and other factors presented in NUREG/CR-6224 should be reviewed before using this correlation.
- As explained in subsection 5.1.6.3, debris bed loadings of microporous insulation debris exceeding microporous-to-fiber mass ratio of 0.2 may result in somewhat nonconservative results from the above NUREG-6224 correlation.

These limitations should be considered for plant-specific applications of the NUREG/CR 6224 head loss correlations.

Impact of Microporous Insulation Debris

A postulated LOCA due to a high-energy pipe break could generate a mixture of fibrous and microporous insulation debris that may be potentially transported to the ECCS pump intake screens. Experiments were conducted to address the head loss behavior due to mixtures of fibrous and microporous debris. In particular, these experiments considered several combinations of microporous insulation debris (i.e., Min-K, Microtherm, Cal-Sil) mixed with fibrous insulation debris and particulate debris.

The microporous tests showed that the contributions to head loss of microporous insulation could be neglected when conditions yielded a microporous mass to strainer surface area ratio of 0.02 lb/ft^2. Scaling of the experimental results to the prototypical conditions can be accomplished by scaling to the actual installed strainers apportioning the microporous loads in the ratio of the flows when more than one strainer is operational.

The microporous tests also showed that it is possible to use the NUREG/CR-6224 head loss correlation to bound the observed test results for mixtures of fibrous and microporous insulation debris when the microporous-to-fiber mass ratio is less than 0.2. For quantities of debris for which the microporous-to-fibrous mass ratio exceeds 0.2, the head loss behavior appears to be dominated by the microporous component, and the NUREG/CR-6224 head loss approximation is no longer applicable.

Use of the NUREG/CR-6224 head loss correlation to approximate the observed head loss behavior due to fibrous and microporous insulation debris requires the specification of a characteristic size and density of the microporous particles. Reasonable agreement with the observed head loss results is obtained when the microporous particulate matter debris is assumed to be in spherical particles, with a characteristic size of 5 μm and a density of 140 lb/ft^3. With these parameters to characterize microporous particles, the NUREG/CR-6224 head loss correlation adequately bounds the observed test data when the microporous-to-fiber mass ratio is less than approximately 0.2. This comparison is shown in Figure 4.2.5.2-2, which presents the NUREG/CR-6224 head loss correlation and the measured head loss results for 6 pounds of fibers at a flow rate of 200 gpm (equivalent to an approach velocity of 0.09 ft/sec) and a water temperature of 60°F.

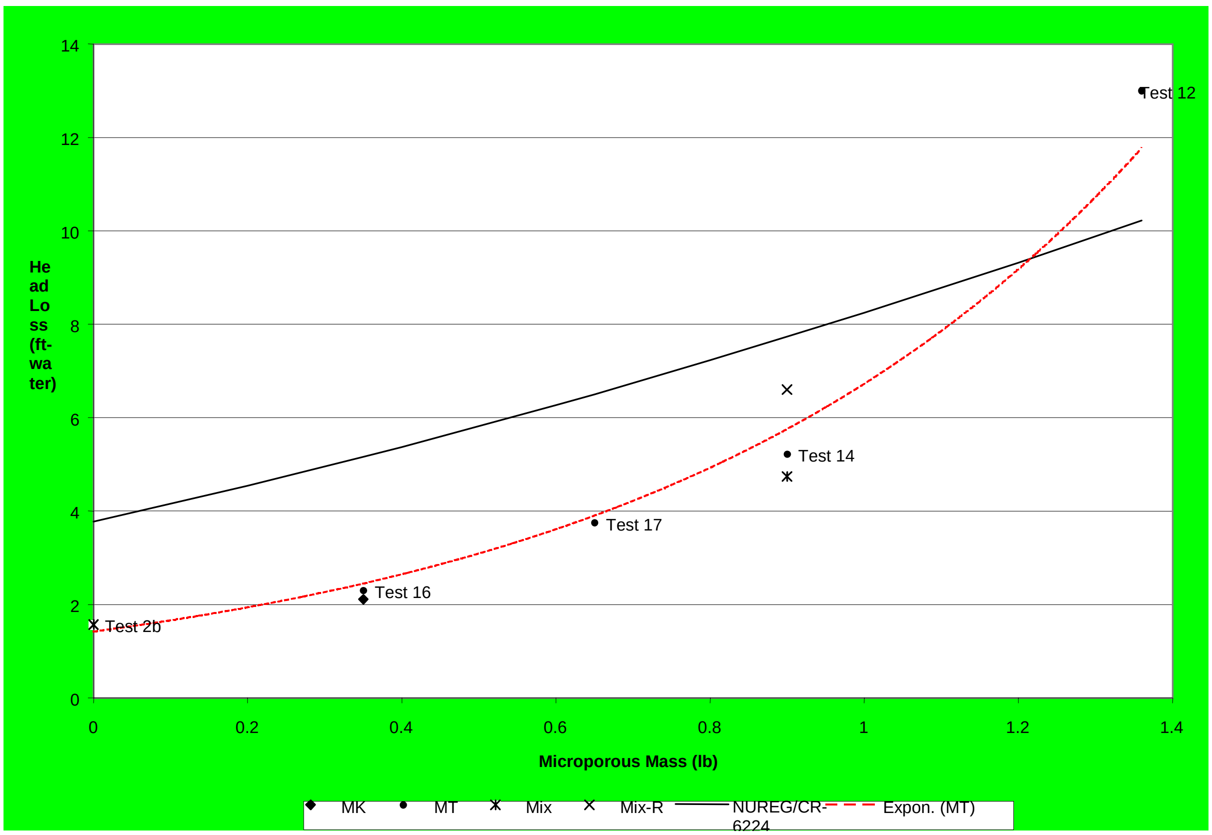
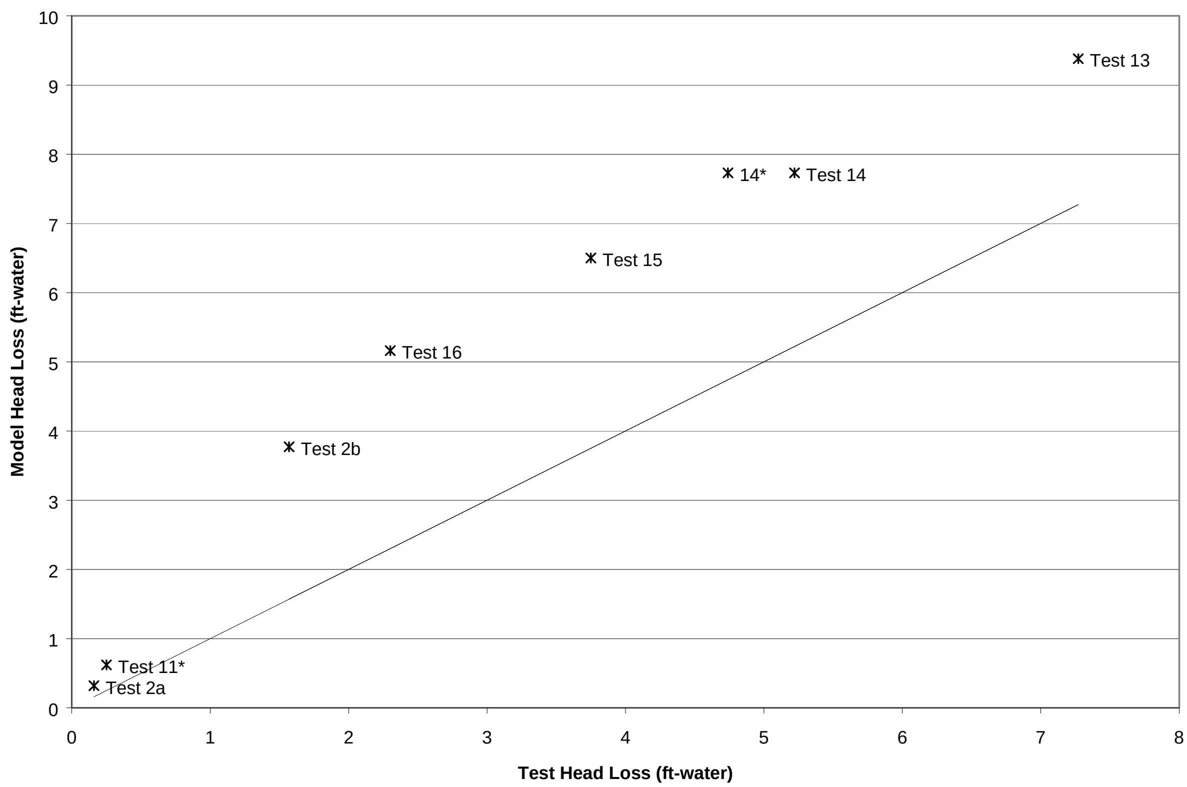


Figure 4-9. Comparison between the NUREG/CR-6224 Head Loss Correlation and the Test Data for 6.0 lb of Fibrous Insulation Debris in the Test Tank

As indicated in the figure, the NUREG/CR-6224 head loss correlation adequately bounds the test data when the microporous-to-fiber mass ratio is less than 0.2 and when the aforementioned parameters are used to characterize the microporous debris (i.e., size and density).

A comparison of the NUREG/CR-6224 head loss correlation with the test data for a microporous-to-fiber mass ratio less than 0.2, including a medium fiber load as well as the applicable test with simulated sludge, is presented in Figure 4.2.5.2-3.



Note: The straight line corresponds to an ideal agreement with the test results.

Figure 4-10. Comparison between the NUREG/CR-6224 Head Loss Correlation and the Test Data when the Microporous-to-Fiber Mass Ratio in the Test Tank is Less than 0.2

As indicated in Figure 4.2.5.2-3, the proposed model of considering that microporous insulation debris may be treated as particulate matter debris, with the NUREG/CR-6224 head loss correlation, bounds the test data when the microporous-to-fiber mass ratio in the tank is less than 0.2. Consequently, estimation of head losses due to mixtures of debris with microporous insulation debris can treat the microporous insulation as a particulate matter debris in the NUREG/CR-6224 head loss correlation for fibrous debris, provided that the microporous-to-fiber mass ratio in the debris bed does not exceed 0.2.

U. S. BWROG Characterization of Combined Debris Head Loss

The U.S. BWROG, while conducting combined debris testing to establish the bases for resolution of the ECCS suction strainer plugging issues, has observed phenomena that may have significant implications for potential resolutions of the ECCS suction strainer issue. In general, the BWROG observations indicate increasing head losses when both fiber loading and corrosion product loading on the strainer are increased together, which is what would be anticipated. A second and more significant observation was not initially expected. If the amount of fibrous debris in the bed is decreased while the amount of particulate material is held constant, the head loss could increase (depending on the ratio of the mass of corrosion products to the mass of fiber) rather than decrease as might be initially thought. This behavior was previously suggested by Vattenfall.

While this phenomenon seems counterintuitive, this finding is consistent with other European experiments. As demonstrated during the Perry events and confirmed by subsequent testing, only a thin bed of fiber is required on the surface of a flat-plate strainer to effectively filter out fine particulate materials that would have otherwise passed through the strainer. The BWROG testing program demonstrated that the highest head losses occur with thin layers of fiber and high ratios of corrosion product mass to fibrous debris on flat-plate strainers.

Physically, a given amount of particulate material results in debris beds that can become increasingly compact and decreasingly porous as the amount of fiber present in the bed decreases. The end result is that a fiber bed just thick enough to bridge all of the strainer holes combined with an inventory of fine particulate materials can result in a very large head loss. Based on the testing performed and current understanding of the likely physical causes, these phenomena would not be expected to proceed beyond the point where the layer of fibrous material is insufficient to fully bridge all of the strainer holes. These observations were made during extensive testing both on fiber only and on debris beds comprising fiber and corrosion products. The iron oxide corrosion products used for these tests had a larger average particle size than that typically present in U.S. BWR suppression pools. Use of the larger-size particulate material was shown to result in a conservative estimate of the combined debris head losses, as larger particles are more likely to be captured in the fibrous bed. The following head loss correlation was documented in the BWROG URG (Reference 41) (Note: Other correlations were developed by replacement strainer vendors.)

$$\Delta h = K_h \mu U t / \left(\rho g d^2\right) \tag{3}$$

where,

Δh	is strainer head loss, ft of water
μ	is viscosity, lb-sec/ft^2
U	is strainer approach velocity, ft/sec
t	is fiber bed thickness, ft
ρ	is water density slug/ft^2
g	is gravitational constant, 32.2 ft/sec^2
d	is inter-fiber spacing, ft

This equation has been simplified to:

$$\Delta h = a + bU \tag{4}$$

where a and b are coefficients dependent on the ratios (Ms/Mf) of different masses of solids (e.g., corrosion products, paint chips, rust flakes, sand, cement dust, calcium silicate, etc.) and fibrous materials assumed to collect on the debris bed.

A significant aspect of this section is that a large head loss can occur with relatively small fibrous loading in combination with a particulate inventory, and that the resolution options must be able to manage or prevent unacceptable strainer head losses. Equations 3 and 4 and the BWROG URG methodology were developed by the U.S. BWROG for specific conditions and should, therefore, be used with caution and reviewed for applicability by the user.

Characterization of Head Loss Due to Reflective Metallic Insulation

Many plants have some reflective metallic insulation (RMI) installed, and there has been significant interest in the behavior of this material. Experiments have been performed to determine how it and other materials react to blast and jet forces, and its transport characteristics. Head loss testing of debris beds comprising RMI, or of mixed beds containing RMI, has been conducted by several organizations, as described in detail in Table 4.2.5.2-2. The topic of RMI debris bed head loss has initiated some disagreement, and it would appear that much of the lack of agreement stems from RMI debris shape, bed morphology, and transport characteristics fundamental to the head loss experiments. For one to evaluate the effect of RMI, the shape and form of RMI reaching the bed, and the predicted morphology of the bed under accident conditions should be carefully evaluated to ensure that the testing and derived relationships properly represent the real situation.

The following observations provide the basis for the method of accounting for RMI contribution to debris bed head loss in the U.S.:

1. The transport characteristics for RMI may be different than other debris, and must be accounted for in predicting the debris bed formation. Depending on the pool turbulence and approach velocities, RMI deposition may not be uniform.

2. If RMI does transport and is deposited on screens/strainers, it will produce head loss. The head loss developed is highly dependent on the type of RMI debris. For example, if a large, intact sheet of metallic foil is deposited over the screen or strainer, it will reduce the flow area significantly and increase the velocity and head loss in the remaining flow area. Based on various results from debris generation testing, RMI debris is expected to be small and crumpled in form, as opposed to large, intact sheets. The head loss characteristics of this type of RMI debris range from benign to small in comparison with that expected from combined fiber/particulate beds.

The BWROG has recommended, in its URG, use of the following equation for determining RMI bed head loss (the equation is valid for head losses under ~ 10 feet H_2O):

$$\Delta h = K_p U^2 t_p \qquad (5)$$

where,

Δh	is head loss, ft of water
K_p	is a constant depending on the type of RMI and strainer
U	is the approach velocity, ft/sec
t_p	is the projected RMI debris bed thickness

A similar relationship has been suggested by the NRC:

$$\Delta P \alpha \frac{S_v(1-\varepsilon)}{\varepsilon^2} U^2 \ N \alpha \frac{L_1 * L_2}{K_t^2} U^2 \left(A_{foil}/A_{str}\right) \tag{6}$$

where,

ΔP	is head loss
L,S	are foil dimensions
K	is inter-foil channel size
U	is approach velocity
N	is number of foil layers

Where there is combined debris consisting of fibrous material, particulate matter or sludge, and RMI, the head loss due to the fibrous and particulate material are expected to dominate. Testing of BWR prototypic strainers has indicated that RMI does not cause significantly different head losses than those caused by fibrous debris and sludge only. The NRC and BWROG research does not indicate the presence of an autocatalytic or synergistic effect between RMI and other debris beds similar to combined fibrous and particulate beds. For mixed RMI and fiber beds, the NRC approach to consideration of RMI head loss is that it should be added (summed) to the head losses expected from other (fibrous and particulate) debris unless it can be demonstrated that this conservative approach is not appropriate.

Other investigators have reported results and conclusions that differ from the above due to considerations associated with the structure of metallic debris beds. The bed structure, as alluded to before, will have a significant impact on the head loss. For example, consider a bed of metallic foils where most of the foils are arranged parallel to the flow direction. One might expect that relative head loss resulting from this configuration with or without other material would be less than other configurations. Consider a bed where most of the foils are deposited perpendicular to the flow. This type of bed configuration will be subject to compression effects, and combined debris would also tend to increase the head loss and bed compression. The realistic situation would probably exist between these two extremes. As previously stated, the bed structure depends on many factors including its shape as generated during the LOCA event, how it is transported (tumbling on floor versus mid-stream suspension), and its formation sequence (mixed deposition of insulation and other debris, tumbling up from bottom or curb, etc.). Again, it is important to carefully consider the plant-specific situation to develop realistic models.

Another form of RMI head loss correlation takes into consideration the pressure drop in RMI debris beds with gap or bypass:

$$\frac{\Delta p}{\frac{\rho w_o^2}{2}} = f_{(R)} \frac{nW}{D} \tag{7}$$

where,

Δp	is the pressure drop
ρ	is the fluid density
w_o	is velocity
$f_{(R)}$	is friction factor
n_w	is path length of fluid traveled in the bed; n is the number of foil layers and W the foil lateral length
D	is the width of the flow channel; depth of foil crumpling

This relationship assumes that pressure drop in a metallic bed behaves analogously to pipe flow. The friction factor, f, depends on bed morphology (structure), and may also contain dependency on debris surface characteristics such as relative roughness, in addition to the Reynolds number, and must be determined experimentally. The correlation is presently limited by the following assumptions:

- The debris has uniform dimensions.
- The debris bed area is independent of thickness.

While investigating the RMI debris head losses, it was observed that the ratio of maximum to minimum head loss for different configurations (flatter RMI debris perpendicular to flow versus parallel to flow) can vary by two or three orders of magnitude.

It should be noted that the variability of different vendor products (e.g., dimpled foils, waffle patterns, or smooth patterns) suggests caution and review of product lines before extrapolating results. In addition, some experimental results indicate that mixtures of foil pieces and fibrous debris can result in significantly higher head losses than would be derived from summing the individual contributions.

Related Methodologies

Several companion methodologies have been developed utilizing the research results and methods discussed above. These methods have been primarily developed for use in calculating the pressure drop across replacement suction strainers, and are discussed in Table 4.2.5.2-2. Typical of these methodologies is one developed that utilizes dimensional analysis for determination of head loss and has been further enhanced to account for bed compression and different strainer geometrical configurations such as would be present in a stacked disc or star strainer. The basic equation is of the following form:

$$\Delta H\ A_s^2\ \rho/QM \left(\nu/d_{if}^2\right)\left[1 + k\ Re\right] = f(\eta) \tag{8}$$

where,

ΔH	is the head loss
A_s	is the surface area
ρ	is the bed density
Q	is volume flow
M	is mass of fiber M_f and mass of sludge
M_s	is kinematic viscosity
d_{if}	is inter-fiber spacing
k	is a constant
Re	is the Reynolds number, $Re = (Q/As)d_{if}/v$
η	is M_s/M_f

4.2.5.2.3 Refinements and Recommendations

Although there are no refinements recommended to reduce the conservatism of the NUREG/CR-6224 correlation itself, there exist potential improvements in head loss modeling:

1. Flat screen assumption – Section 3.7 recommends using the assumption of a flat screen for the head loss analysis. For most screen designs, there is little or no improvement to be had by changing to another assumption. However, for some screen designs, alternate geometry is used and conservatism could be reduced by modeling the screen geometry more accurately.

2. Uniform debris deposition – Section 3.7 recommends using the assumption of uniform debris deposition for the head loss analysis. For most screen designs, there is little or no improvement to be had by changing to another assumption. However, for some screen designs, debris will not be deposited in a uniform manner. If the uniform debris deposition assumption is not used, the screen design being evaluated will need to be tested or analyzed to determine the actual debris deposition. Using this information, more realistic assumptions can be made regarding the screen area available and the thickness of the resulting debris bed.

It is noteworthy that the two refinements discussed above are two of the areas in which alternate strainer designs offer an advantage over standard screen designs. Typically, alternate strainer designs are not flat screens. If this is the case, depending on the geometry, uniform debris deposition will not occur. In these cases, using the NUREG/CR-6224 correlation will be overly conservative.

For alternate strainer designs, new head loss correlations will have to be developed. These correlations should be developed by the designer and/or vendor of the new sump screen, and should be used when performing the head loss analysis.

5 REFINEMENTS IN ADMINISTRATIVE CONTROL AND DESIGN

In addition to analytical refinements, licensees may choose to consider administrative control refinements, design refinements, or a combination of administrative control and design refinements, to enhance post-accident sump performance. This section describes some of these refinements that are generically applicable to all PWRs. Licensees may identify additional design or operational refinements that are applicable to their specific plant.

5.1 DEBRIS SOURCE TERM

A number of design and operational refinements can contribute to the improvement of the debris source term, with a consequential reduction in head loss across the sump screen resulting from debris accumulation. Five categories for design and operational refinements are examined.

1. Housekeeping and FME programs – Implementing or improving housekeeping and foreign material exclusion (FME) programs has the potential to reduce the debris source term. This operational refinement primarily addresses latent debris concerns (as described in Section 3.5).

   Housekeeping and FME programs reduce the amount of latent debris inside containment by removing as much foreign material as possible between the end of outage activities and plant startup. Many FME programs that are in place at plants focus on exclusion of foreign materials from the reactor itself and supporting systems located inside and outside containment. Since the containment is a system in itself and is directly connected to the ECCS during the recirculation mode, it is reasonable to include containment housekeeping as part of a plant FME program.

   Housekeeping and FME programs should remove all foreign materials from containment that have the potential to be transported to the sump. These materials include, but are not limited to:

   - Dirt and dust
   - Tape
   - Temporary-use outage equipment
   - Temporary-use signs
   - Protective clothing
   - Trash bags
   - Cable ties
   - Rope
   - Tarps

   Refer to NEI 02-01 (Reference 2) for a more complete list of these items.

   A significant reduction in the amount of foreign material can be accomplished by simply picking up (by hand) and removing foreign material at the end of the outage. Large-scale cleaning activities such as pressure washing, vacuuming, and mopping are effective at removing dust and dirt from surfaces inside containment such as floors, walls, junction boxes, and other equipment. A subsequent cleanliness walkdown is recommended, to verify that foreign materials have been removed and perform final cleaning activities.

It is recommended that, if housekeeping or FME programs are implemented, appropriate procedures be designed to ensure a high level of performance from the programs. Of course, it is necessary to integrate FME and housekeeping activities into outage schedules.

2. Change-out of insulation – Change-out of insulation is a highly effective method to improve the debris source term and the resulting head loss across the sump screen when sufficient quantities of problematic insulation are located inside containment. A generic strategy is to remove problematic insulation types and replace them with reflective metallic insulation (RMI). Therefore, it is unlikely that plants using all RMI on the RCS would have a significant benefit from change-out of insulation. One exception for these plants would be if problematic insulation types are used on components besides the RCS. Problematic insulation types include, but are not limited to the following:

   - Calcium silicate
   - Microporous
   - Fibrous insulation (all types)

   Although this refinement is highly effective in reducing the debris source term, there are significant drawbacks to its implementation. Some of these concerns are described below:

   - Other analyses may need to be evaluated, as pipe stress and seismic analysis, heat loads, etc.

   - There is a direct cost associated with the disposal of used insulation materials.

   - There are possible health hazards associated with removing insulation materials such as asbestos. Materials such as this present both biological and radiological hazards and must be dealt with accordingly.

   - It may be necessary to extend a plant outage to remove the problematic materials, depending on the quantity and composition of the insulation.

   - Consequences of insulation change-out, such as thermal performance reduction and changes to pipe stress and seismic analyses, must be evaluated.

- The new insulation materials must be consistent with the plant's licensing basis, or the licensing basis must be modified.

The effectiveness of change-out of insulation should be quantified by analyzing the changes in sump screen head loss using the methods presented in this document.

3. Modify existing insulation – Modifying the existing insulation may reduce the debris source term by increasing the destruction pressure of the insulation and reducing the propagation of damage. Typically, modification is accomplished by adding metal encapsulation or jacketing, while leaving the insulation in place. While this method does offer the possibility of reducing the debris source term while reducing the cost and some potential hazards associated with debris change-out, there are elements to this approach that should be considered carefully. These include, but are not necessarily limited to:

- Review available and applicable test data.

- Additional testing may be performed to determine the destruction pressure of insulation with protective jacketing or encapsulation.

- Other analyses may need to be addressed, such as, pipe stress and seismic analysis, heat load, etc.

4. Modify other equipment or systems – Some benefit may be gained in the debris source term for some plants by modifying other equipment or systems. This option will be less effective than change-out or modification of existing insulation systems. However, in some cases it may be worthwhile to remove or modify equipment such as:

- Equipment tags and other signs
- Sealants (e.g., silicone)
- Fire and radiant barriers
- Elastomer-coated conduit
- Other materials, such as Teflon-coated light bulbs

The list above is not an exhaustive list. Plants should review their containments for possible debris source modifications.

Changes to non-insulation systems should be examined on a plant-specific basis and should be considered in the context of the entire sump performance evaluation. For example, it is unlikely that items such as light bulb covers would be major contributors to the debris source term, when considered along with insulation debris.

5. Modify or improve coatings program – Coating systems used inside containment can be divided into two categories: DBA-qualified/Acceptable coatings and unqualified coatings. DBA-qualified coatings have very high destruction pressures and the corresponding zone of influence is relatively small as compared to the ZOIs for insulation. Since DBA-qualified/Acceptable coatings should make a very small contribution to the debris source term, modifying this type of coating system would have no benefit.

   Non-DBA-qualified coating systems are used extensively in some containments. Since these coatings are assumed to fail when subjected to the post-accident environment, they can be a significant contributor to the debris source term. In all cases, replacing DBA-unqualified/Unacceptable coatings with a DBA-qualified/ Acceptable coating system will be of benefit to the sump performance analysis. The benefit of replacing non-qualified coatings with qualified coatings should be quantified based on plant-specific information and compared to other approaches to determine which is most cost-effective.

5.2 DEBRIS TRANSPORT OBSTRUCTIONS

This section provides mechanical design information for physical debris barriers that may assist in the mitigation of debris movement to the containment sump.

5.2.1 Floor Obstruction Design Considerations

The introduction of physical barriers on the floor will help reduce total debris movement toward the containment sump. Introduced floor barriers (curbs) are capable of stopping or redirecting floor debris in such a manner that the debris loading on the recirculation sump can be reduced (Reference 54). Curbs may be incorporated in the design at or near the sump or may be utilized to isolate debris closer to its source. Debris stopped behind a barrier is likely to remain there if flow velocities and turbulence are insufficient to lift it over the barrier. If the barrier does not cover the entire cross-section of the flow, its effectiveness may be reduced significantly.

5.2.1.1 Test Results

Tests were conducted to ascertain the required velocity and turbulence necessary to lift debris over curbs with the results reported in Reference 55. Reference 55 documents that, assuming a 2-inch curb is introduced (although a higher curb increases conservatism and the ability to trap additional material), for the insulation materials listed in Table 5-1, the velocities shown are required at the curb to lift the debris to pass over the curb. Three different turbulence-producing configurations were tested and the lowest, “Lift at Curb Velocity,” is reported in Table 5-1. The velocities listed are typically for the smallest debris size tested and are specified in the tabulation.

Table 5-1. Test Results for "Lift at Curb Velocity"

Insulation Type	Size or Description	Lift at Curb Velocity (ft/sec)
Nukon	1 in.	0.22
Thermal Wrap (Fiberglass)	4 in x 6 in	0.22
Kaowool	4 in x 6 in	0.25
Stainless Steel RMI	1/2 x 1/2 in.	0.30
Paint Chips	From 1 x 1/2 to 1/8 x 1/8 in. and 15-mil thickness	0.5
Marinite	1 x 1 in.	Not measured but expected to be > 0.5

Based on the inventory of insulation types and calculated post-accident flow velocities, the placement of a curb will be optimized in locations where the local velocity is less than in the test results above. Alternatively, the location of curbs in flow regimes of less than 0.20 ft/sec will limit movement of all expected debris types.

5.2.2 Debris Obstruction Rack Design Considerations

The placement of physical barriers within the flow path, when done correctly, may assist in the mitigation of total debris movement without impeding water flow to the containment sump. Debris racks may be incorporated in the design at or near the sump or may be utilized to isolate debris closer to its source. If the barrier does not cover the entire cross-section of the flow, its effectiveness will be reduced significantly. A permanent or a moveable design may be used, depending on the expected personnel traffic and accessibility limitations introduced by the design. A debris rack may also be used in lieu of a curb within the flow path to minimize the potential trip hazard or to better accommodate expected equipment maintenance and movement requirements. To be effective, the location of the barrier must be within a region where local velocities exceed the incipient tumbling velocity of the debris inventory. Debris obstructions/interceptors should be designed to the same structural considerations as the sump strainer. These barriers should take into account water hold-up behind the barriers. See the test results below.

5.2.2.1 Test Results

Tests were conducted with the results reported in Reference 55. The value listed in Table 5-2 for each insulation type is the lowest tumbling velocity recorded from the University of New Mexico floor transport tests for which there was debris movement. The "Incipient Tumbling Velocity" refers to the minimum fluid velocity (averaged over the flume cross-section) required to induce tumbling or sliding of the debris fragments on the flume bottom. Three different turbulence-producing configurations were tested and the lowest incipient tumbling velocity is reported. The velocities listed are typically the smallest debris size tested as indicated in Table 5-2.

Table 5-2. Test Results for a Floor Transport

Insulation Type	Size or Description	Incipient Tumbling Velocity (ft/sec)
Nukon	1 in.	0.06
Thermal Wrap (Fiberglass)	Fragments, smaller than 4 in x 6 6 in	0.07
Kaowool	Fragments, smaller than 4 in x 6 6 in	0.09
Aluminum RMI	2 in^2 crumpled or flat	0.2
Stainless Steel RMI	1/2 x 1/2 in.	0.2
Paint Chips	From 1 x 1/2 to 1/8 x 1/8 in. and 15-mil thickness	0.4
Marinite	1 x 1 in.	0.77

Based on the inventory of insulation types and calculated post-accident flow velocities, the placement of a debris rack will be optimized in locations where the local velocity is greater than the test results above.

5.2.2.2 Debris Rack Grating Size

Too large an opening will not capture significant debris and thus be ineffective. As concluded in Reference 55, large debris will probably not be transported and therefore, little debris would be expected to be captured. Too small an opening will potentially cause a debris bed buildup, leading to a decrease in flow-through rates and consequently either increasing local flow velocities in other regions (and picking up settled debris) or damming upper levels, causing a drop in downstream levels.

Typically, debris racks in the range of 1 x 4 inches to 1 x 1 inch have been used. Based on the debris generation tests conducted and documented in Reference 54, a high percentage of the RMI debris exceeded these sizes. For fibrous debris, Reference 54 tests indicated that the amount of debris characterized as large generally had an equivalent weight to the amount of fines and small fibers generated. Thus, there is potential for collecting significant debris.

5.3 SCREEN MODIFICATION

In evaluating post-accident sump screen performance, a licensee may determine that it is desirable to modify their existing sump screen. There are several general sump screen designs that a utility may consider for implementation. Factors to be evaluated and features of the designs are discussed below.

5.3.1 Considerations for Passive Strainer Designs

A passive strainer design is one that requires no movement or actuation to perform its design function. Typically, strainers of this design have large surface areas. The large surface area provides the ability to collect large amounts of debris on the strainer face, while sustaining a sufficiently low head loss across the sump screen/debris bed combination that $NPSH_{AVAILABLE}$ is greater than $NPSH_{REQUIRED}$.

Passive strainer designs have several favorable technical considerations.

1. There is an existing body of head loss test data that may be conservatively applied to most hardware designs for several types of debris and debris combinations.

2. Sizing of passive strainers is a relatively straightforward application of existing head loss correlations, such as those given in NUREG/CR-6224.

3. Structural evaluations also involve a relatively straightforward application of standard structural analysis methods and techniques.

4. The design may be modular, facilitating both manufacturing and installation of the modules. Also, a modular design allows expansion of strainer surface area, should the need arise.

5. The applicability of available test data, sizing criteria, commonly accepted structural analysis techniques and modular design, coupled with the passive nature of the design, provide high reliability. Passive strainers will work anytime that flow is initiated through the strainer.

Additional considerations for passive strainers, particularly large passive strainers, include:

1. The containment design may limit the surface area of a passive strainer that can be installed without containment modifications.

2. Large passive strainers may infringe on and limit use of floor space previously used for other purposes.

5.3.2 Considerations for a Backwash Strainer Design

A backwash strainer is a design that allows for self-cleaning by reversing water flow to dislodge debris from the strainer face, thereby reducing the head loss when recirculation flow is reinitiated. Self-cleaning is a desirable feature.

Additional considerations for backwash strainers include:

1. This design requires a source of fluid, and its associated motive force, to perform the backwash function. This fluid may be either water or air. The motive force may be provided by a pump, compressor, or pressurized tank.

2. A power source is needed to support the operation of this design. A power source is needed to actuate valves, pumps, or compressors to initiate and/or terminate the backwash sequence.

3. As with all strainers, backwash strainers require structural evaluations. In addition to the seismic loading that all strainer designs must be designed to withstand, backwash strainers must withstand loads associated with normal (recirculation) flow and debris loading, as well as the reverse flow and impulse loading associated with shedding of debris.

4. Since there are moving parts in a backwash strainer design, the failure of critical components should be addressed in the design; redundancy and separation of trains should be considered.

5. Since backwashing of the strainer is based on the head loss across the debris bed/strainer reaching a predetermined value, instrumentation is needed to determine when that value is reached. This necessarily involves calibration and uncertainty analysis to ensure that adequate margin is available to initiate backwash before sump blockage affects either ECC or CS operation.

6. A backwash strainer may be required to undergo surveillance testing to demonstrate that it will work as designed. This testing would require planning, procedures, and personnel to conduct the surveillance. Also, surveillance testing may impact ALARA dose.

7. Reliability of active components is a design concern for backwash strainers. The inadvertent or spurious actuation of components of a backwash strainer may result in a forced shutdown. Similarly, the failure of a component to operate during an at-power surveillance test may cause a plant to shut down.

5.3.3 Considerations for an Active Strainer Design

An active strainer is a design that incorporates active components to maintain flow to the sump. Typically, this design has some components that are powered continuously once recirculation flow is initiated. Continuous cleaning of the strainer surface area is a desirable feature of an active strainer design.

Active self-cleaning strainers have several favorable technical considerations.

1. Active self-cleaning strainers may be relatively small compared to passive systems and therefore minimize the impact on containment floor space.

2. Active self-cleaning strainer head loss and performance may be independent of debris type and quantity.

3. Active self-cleaning strainers may avoid uncertainties related to water chemistry, chemical effects, debris, transportability, and long term bed compaction and erosion.

Additional considerations for active strainers include:

1. Currently, there are no active strainer applications for either BWRs or PWRs. It may be expected that several experimental studies will need to be undertaken to support the implementation of an active strainer design.

2. The design of the active strainer will need to account for characteristics of PWR insulation debris.

3. A power source may be needed to support the operation of this design. The power source may be external to the strainer, such as a motor, or internal to the strainer, such as a turbine that uses the water flow through the strainer to drive the strainer cleaning mechanism.

4. As with all strainers, active strainers require structural evaluations. In addition to the seismic loading that all strainer designs must be designed to withstand, active strainers must withstand loads associated with the normal (recirculation) flow, loads imposed on the strainer structure by the cleaning mechanism, and debris loading.

5. Since there are moving parts in an active strainer design, reliability of active components is a design concern. Specifically, redundancy and separation of trains of the cleaning mechanisms should be considered.

6. An active strainer is actuated upon a signal that the strainer is required to be in operation. An actuation signal or an instrument output signal is needed to initiate the active portion of the strainer cleaning mechanism. This necessarily involves a signal analysis and uncertainty evaluation to ensure that adequate time is available between identification of need for the strainer and actuation of the cleaning mechanism. Margin must be available to initiate backwash before sump blockage affects either ECC or CS operation.

7. The cleaning action of active strainers may induce ingestion of debris into the recirculating flow that otherwise might be captured on the debris bed. This ingested debris may present additional considerations for downstream effects evaluations.

8. An active strainer may be required to undergo surveillance testing to demonstrate that it will work as designed. This testing would require planning, procedures, and personnel to conduct the surveillance. Also, surveillance testing may impact ALARA dose.

5.3.4 Summary

In assessing post-accident sump screen performance, licensees may choose to change the sump screen. Three possible sump screen designs were identified, along with their potential benefits and related concerns for their design, installation, and operation. It is expected that licensees will conduct a design review as an integral step in their sump screen modifications. The benefits and concerns listed in this section are useful in considering strainer design options, and provide an initial set of criteria for conducting a design review. NRC review of new strainer designs may require experimental data demonstrating performance of the design.

6 RISK-INFORMED EVALUATION

6.1 INTRODUCTION

In SECY-02-0057, "Update to SECY-01-0133, 'Fourth Status Report on Study of Risk-Informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendation on Risk-Informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria)," the staff recommended the development of risk-informed approaches to technical requirements in 10 CFR 50.46 (and related provisions) concerning LOCA acceptance criteria and evaluation models. In its March 31, 2003 SRM, the Commission directed the staff to undertake rulemakings, one of which would develop a proposed rule to allow, as a voluntary alternative, a redefinition of design basis maximum break size.

The NRC supports consideration of licensee requests for exemptions to these requirements, as allowed by 10 CFR 50.12, as a means to facilitate the rulemaking process. In a March 4, 2004 letter to NEI, NRC opened the possibility for risk-informing portions of the evaluation process for addressing GSI-191 concerns.

> "…the NRC staff plans to discuss, in public meetings, the use of current or planned work to risk-inform Title 10, *Code of Federal Regulations* Section 50.46, "Acceptance criteria for emergency core cooling system for light-water nuclear power reactors," as a suitable technical basis for defining a spectrum of break sizes for debris generation and containment sump strainer performance."

A risk-informed option for GSI-191 resolution is discussed in this section. This process (Option B of Figure X) allows for use of an alternate maximum break size in analyses that demonstrate compliance with the long-term cooling requirement of 10 CFR 50.46.

Implementation of Option B involves two separate analysis steps:

1) Design Basis Analysis using Alternate Break Size
2) Demonstration of Beyond-Design-Basis Mitigation Capability

The design basis analysis under Option B is performed in the same manner as that called for under Option A and described in Sections 3, 4 and 5 with the exception that the maximum break size considered in the design basis analysis is less than the double-ended rupture of the largest pipe in the reactor coolant system called for in 10 CFR 50.46. Section 6.2 provides additional guidance on performance of the design basis analysis under Option B. Table 6.2-1 provides a summary of modifications to guidance in Sections 3, 4 and 5 to perform the design basis analysis under Option B.

In implementing the Option B approach and use of an alternate break size, it is necessary to demonstrate that some degree of mitigation capability is retained for break sizes between the new maximum break size and the double-ended guillotine break of the largest pipe in the reactor coolant system. This "beyond-design-basis" analysis is performed using more realistic analysis methods and assumptions and allows credit to be taken for non-safety SSCs and operator actions. In addition, relaxation of the acceptance criteria applicable to design basis analyses is acceptable. Section 6.3 provides guidance on an appropriate set of modifications to the analysis methods and assumptions described in Sections 3, 4 and 5 for use in the Option B analysis to demonstrate mitigation capability. These modifications are summarized in Table 6.3-1.

In addition to the analysis steps described in this section, the preparation of a separate regulatory basis document will be necessary to support the application of the Option B approach. Guidance for preparation of the regulatory basis will be provided in a separate document.

6.2 RISK-INFORMED DESIGN BASIS ANALYSIS

The analysis of recirculation system performance under Option B is performed in the same manner as described in Sections 3, 4 and 5 of this document, except that the maximum size of RCS breaks to be considered is set by the "Alternate Break Size." The range of secondary side break sizes that should be considered is unchanged under Option B. The "Alternate Break Size" for use under Option B is described in section 6.2.1.

6.2.1 Alternate Maximum Break Size

(Alternative break size, established as effective flow area, to be determined)

6.2.2 Modification of Break Locations to be considered

The use of an alternate maximum break size has no impact on the range of break locations to be considered. As discussed in Section 3, a full range of break locations should be assessed to determine the limiting location. The use of an alternate maximum break size could impact the limiting location of the break compared to analyses performed under Option A.

6.2.3 Modification of Break Configuration

The maximum break size to be considered for a given primary-side piping location is the minimum of either the Alternate Break Size established in section 6.2.1 or the maximum attainable effective break area.

Example:

Consider a 6" schedule 160 pipe. The transverse internal area of this pipe is 21.15 in^2. The maximum attainable effective break area for this pipe is 2 times this value, or 42.30 in^2 (assuming a source high-energy flow from both directions). This value would be used for the postulated break locations in this pipe in lieu of the alternative maximum break size.

6.2.4 Modifications to Zone of Influence Calculations

The guidance in Section 3.4.2 on determination of the zone of influence for debris generation presumes a DEG break. For DEG breaks, a spherical zone of influence is conservatively postulated.

For large bore piping, postulation of a break size less than the DEG break area would indicate a limited-displacement circumferential break or a longitudinal break, i.e., "split break". This difference can be accounted for in one of the following ways.

a) ZOI Based on a Hemisphere

The zone of influence for split breaks can be simulated as a hemisphere with radius determined by the destruction pressure of the insulation that would be affected by the postulated break. From Table 3.4.2-1, for unjacketed Nukon insulation[1], the hemisphere would have a radius of 12.1 times the effective diameter, D, of postulated break or 12.1D.

b) ZOI Based on a Sphere

Because a worst-case break orientation can be difficult to determine, an alternative to assuming a hemispherical ZOI is to translate the hemispherical volume into an equivalent volume sphere. For the case of unjacketed Nukon insuation, this translation leads to a sphere with a radius of 9.6D.

Additional guidance is provided in Section 4 for the use of the following refinements to the guidance given above:

1. The use of debris specific zones of influence, and,
2. The use of directed jets to evaluate damage to insulation and coatings

As noted above in item (a), however, for large bore piping and a postulated break size less than the DEG break area, the use of a directed jet for debris generation may require the determination of a worst-case break orientation.

6.2.5 Modifications to Event Timings and Conditions

Consideration should be given to the potential impact of the Alternate Break Size on event timings, thermal/hydraulic conditions and NPSH requirements. Use of the

[1] As described in Section 3.4.2.2, "Selecting The value of the ZOI," the ZOI value used in a plant-specific calculation depends upon the destruction pressure of the insulation in the region of the break. Nukon insulation is used as an example here as this was the insulation type that was used to define the sample calculation described in Section 3.4.2.6, "Sample Calculation", of the Baseline Evaluation.

Alternate Break Size in lieu of a full DEG break on the main loop piping will affect key event timings, such as lower containment fill-up and the timing of transfer to recirculation from RWST injection.

Table 6.2-1

Design Basis Analysis Methodology

Comparison between Option A and Option B

	Option A	**Option B**
Maximum Break Size	Up to full DEG of largest pipe in reactor coolant system	Up to Alternate Maximum Break Size as defined in Section 6.2.1
Break Locations	No Change	
Break Configuration	Full DEG	Minimum of full DEG or Alternate Maximum Break Size

6.3 ANALYSIS TO DEMONSTRATE MITIGATION CAPABILITY

In implementing the Option B approach and use of an alternate break size, it is necessary to demonstrate that some degree of mitigation capability is retained for break sizes between the new maximum break size and the double-ended guillotine break of the largest pipe in the reactor coolant system. This analysis to demonstrate mitigation capability (DMC) is performed using more realistic analysis methods and assumptions and credit can be taken for operation of non-safety systems, structures and components as well as expected operator actions. In addition, modification of the acceptance criteria applicable to design basis analyses is allowed.

The list of potential modifications to the set of conservative methods and assumptions used in the design basis analysis is large. In order to simplify the DMC analysis process the following sections identify a recommended set of modifications to methods and assumptions described in Section 3 through 5.

6.3.1 Break Sizes

Break sizes that need to be considered in the DMC analysis cover the range from "Alternate Break Size" identified in Section 6.2.1 up to a full DEGB of the largest attached piping.

6.3.2 Break Locations

Primary side piping whose maximum attainable break area is less than or equal to the "Alternate Break Size" will have already been addressed as part of the design basis analysis and can be excluded from further consideration as part of the DMC analysis. Any postulated secondary side break locations will also have been addressed as part of the design basis analysis and can be excluded from the DMC analysis. Consequently, all high energy piping locations except for main loop piping are fully addressed as part of the design basis analysis.

For the remaining break locations, guidance provided in Standard Review Plan 3.6.2, *Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping*, and MEB 3-1, *Postulated Rupture Locations in Fluid System Piping Inside and Outside Containment*, should be used to identify postulated primary side break locations.

6.3.3 Break Configuration

Circumferential breaks should be assumed to result in pipe severance and separation amounting to at least one-diameter lateral displacement of the ruptured piping sections unless physically limited by piping restraints, structural members, or piping stiffness as may be demonstrated by limit analysis. Limited pipe displacement at the break location, line restrictions, flow limiters, positive pump-controlled flow, and the absence of energy reservoirs may be taken into account, as applicable.

Existing plant-specific dynamic loads analyses for postulated primary side breaks should be utilized to assist the DMC analysis.

6.3.4 Analysis Assumptions

In performing the DMC analysis, consideration should be given to relaxation of analysis assumptions used in the design basis analysis. In general, the DMC analysis can use nominal expected conditions in lieu of bounding values used in DBA calculations.

For simplicity and ease of calculation, DBA analysis assumptions and guidance in Sections 3, 4 and 5 may be used. Any modifications to DBA analysis assumptions for use in the DMC analysis, to account for nominal expected conditions, should be identified.

Key DBA assumptions that can be considered for modification and use in the DMC analysis include:

- No coincident loss of offsite power
- No assumed limiting single failure

In addition, nominal expected conditions can be considered in a number of areas, including:

- RCS initial power and temperature
- Decay heat
- ECCS flow and temperature
- Containment spray flow and temperature
- Latent debris source term
- More realistic assumptions for debris transport to the sump

An important allowance in the DMC analysis is credit for operation of non-safety equipment and for expected operation actions taken to mitigate the postulated LOCA event. The actions and operations that can be credited will be plant-specific, but could include:

- Credit for non-safety active screens, screen backwash systems or similar modifications to containment sump screen design
- Operator actions, as directed by emergency procedures (e.g., termination of containment spray flow, ECCS flow adjustments)

6.3.5 Applicable Success Criteria

Breaks greater than the maximum break size considered in the design basis analysis are "beyond-design-basis." The applicable criteria to demonstrate retained mitigation capability for long-term cooling capability in the DMC analysis are:

1. Positive NPSH margin is maintained for the minimum number of ECCS pumps necessary to demonstrate adequate core cooling flow
2. Demonstration of adequate containment cooling capability to provide assurance that the containment boundary remains intact

The first criterion can be met by demonstrating that adequate flow to the core is maintained to remove decay heat. This demonstration can be met by ensuring NPSH margin is maintained for one or more moderate to high-capacity ECCS injection pumps (e.g., low-head RHR pumps). A single-failure of ECCS trains does not need to be considered.

The time-variable nature of required and available NPSH can be considered. Limited operation in cavitation (negative NPSH margin) can be considered.

In the calculation of available and required NPSH, the following should be considered:

- Nominal containment sump temperatures and levels
- Nominal Containment backpressure
- Nominal ECCS flow (credit may be taken for operator actions to control ECCS flow and match decay heat removal requirements)

The second criterion can be met through credit taken for one or more heat-removal pathways, including containment fan coolers.

7 ADDITIONAL DESIGN CONSIDERATIONS

There are additional considerations beyond head loss that are to be taken into consideration when evaluating the post-accident performance of the containment sump screen. These considerations include:

1. Structural analysis of the containment sump
2. Upstream effects
3. Downstream effects
4. Chemical effects

Guidance is given in the following sections for evaluating each of these considerations.

7.1 STRUCTURAL ANALYSIS OF CONTAINMENT SUMP

Following the analysis of the debris generation, debris transport, and debris head loss across the strainer screen, a structural evaluation of the strainer screen assembly shall be performed based on the predicted debris head loss. Using the strainer flow rates and the debris loading, the clean strainer head loss combined with the debris head loss will predict the maximum differential pressure across the strainer screen assembly. This head loss is less than or equal to the allowable head loss at which the ECCS pumps and CS pumps would be credited to deliver the required cooling water flow. Many existing PWR strainer screen assemblies have a geometry of a rectangular box, with essentially four vertical flat screens, constructed of grating and wire mesh screening. Most of the existing PWR strainers were designed for 50 percent blockage with essentially no differential pressure across the screen assembly. As such, many of these simple rectangular strainer assemblies were not designed to accommodate any significant differential pressure. Along with the evaluation of the overall structural integrity of the strainer assembly, it is very important to evaluate the attachment of the wire mesh screen to the strainer assembly frame. The wire mesh tends to stretch and, depending on the attachment method, gaps could form during debris loading that would allow the debris to bypass the wire mesh. It should be noted that all of the replacement BWR strainers used perforated plate material instead of the original wire mesh.

Materials selected for fabrication of new strainers should take into account the post-accident environment in which they will be required to operate. Corrosion-resistant materials are recommended.

The existing strainers should have been designed to the specific plant seismic requirements. The seismic design is typically a pre-LOCA environment with no debris loading and a dry containment. As stated in Regulatory Guide 1.82, Revision 3, subsection 1.1.1.8, hydrodynamic loads on the strainer may need to be evaluated. A review of the design basis of the containment should provide guidance in the design requirements of the strainer in the long-term post-LOCA environment. When evaluating long term, many days or months, operation of the strainer in a submerged environment with debris loading, a seismic event could introduce sloshing of the water within the flooded containment. This could introduce additional structural loading onto the strainer.

In addition to the above structural issues, one may wish to allow for structural margin in the strainer design. If additional NPSH margin is gained by a combination of changes in the ECCS pump requirements, CS pump requirements, containment water level, containment overpressure, or debris source term, this could result in an increase in the differential pressure across the strainer. A plant would not want structural design of the strainer to be the weak link in resolving the GSI-191 issue.

Finally, the replacement BWR ECCS strainers that were installed during the 1990s were designed to different structural requirements than would be required for the PWRs. In BWRs, very large hydrodynamic loads are created in the suppression pool during the LOCA blowdown and safety relief valve discharges, resulting in long-term chugging in the suppression pool. As such, the BWR strainer designs incorporated structural features that may not be applicable or needed in the PWR design.

7.2 UPSTREAM EFFECTS

Evaluation of the containment sump should include a review of the flow paths leading to the sump screen itself. The containment condition assessment as described in NEI 02-01 provides guidance on this review. The concern to be addressed for upstream effects is the hold-up of inventory away from the containment sump, possibly "starving" the sump of flow. Thus, this review should look for locations where debris might collect and either retard or block the flow to the sump.

The following parameters are important to the evaluation of upstream effects:

1. Both the containment design and the postulated break location. These two items determine the flow path and the hydraulic characteristics of the flow path to the containment sump.

2. The postulated break size and insulation materials in the ZOI about the break. These two items determine the debris characteristics to be considered, as well as the flow rate to the sump.

The parameters identified above provide a basis to evaluate hold-up or choke points in the flow field within containment upstream of the containment sump.

Examples of locations to look for and evaluate for hold-up of liquid upstream of the sump screen include:

1. Narrowing of hallways or passages. Large pieces of debris may gather on the floor in these areas and form a debris "mound."

2. Gates or screens that restrict access to areas of containment such as behind the bioshield or crane wall. Again, medium- to large-sized debris may form behind the screen or grate, restricting flow to the containment sump from behind the bioshield or crane wall.

3. Refueling canal drain to lower containment. Most plants have a drain path from upper containment to the refueling canal to the elevation of the containment sump. Depending on break location and insulation materials used at a plant, significant debris may be generated from a postulated break, then transported to the upper containment and on to the refueling canal to be collected on the refueling canal floor drain. The collection of debris on the floor drain should be evaluated to determine if this path to the containment sump may be blocked.

The items listed above are typical areas of concern that are generally applicable to all containments. As noted previously, however, each containment design has unique geometric features, as well as a plant-specific insulation installation. An upstream effects evaluation should include and address these plant-specific features.

7.3 DOWNSTREAM EFFECTS

Evaluation of the containment sump should include a review of the flow paths downstream of the emergency core cooling (ECC) and containment spray (CS) systems. The concerns to be addressed for downstream effects are:

1. Blockage of flow paths in equipment; for example, containment spray nozzles or tight-clearance valves.

2. Wear and abrasion of surfaces; for example, pump running surfaces, heat exchanger tubes and orifices.

3. Blockage of flow clearances through fuel assemblies.

In general, a downstream review should broadly consider flow blockage in the ECC and CS flow paths, as well as examining wear and abrasion in systems, structures, and components in the ECC and CS flow paths that are important to the long-term cooling function.

A logical start for the evaluation is to consider the flow clearance through the sump screen. This determines the maximum size of particulate debris that will pass through the sump screen and enter the ECC and CS flow paths. If passages and channels in the ECC and CS downstream of the sump screen are larger than the flow clearance through the sump screen, blockage of those passages and channels by ingested debris is not a concern. If there are passages and channels equal to or smaller than the flow clearance through the sump screen, then the potential for blockage exists and an evaluation should be made to determine if the consequences of blockage are acceptable, or if design modifications are warranted.

Similarly, wear and abrasion of surfaces in the ECC and CS should be evaluated, based on the flow rates to which the surfaces will be subjected and the grittiness or abrasiveness of the ingested debris. The abrasiveness of the debris is plant-specific and depends on the insulation materials that become debris. For example, fiberglass is a known to be an abrasive material.

Wear and abrasion of pumps due to ingestion of debris may have been addressed by the pump manufacturer. Licensees should request information and/or test data from the pump vendor regarding the ability of specific pumps to perform with debris in the pumped flow. Other sources of information may include information generated to support the closeout of USI A-41 such as NUREG/CR-2792 (Reference 58).

7.4 CHEMICAL EFFECTS

Pressurized water reactor (PWR) containment buildings are designed to both contain radioactive material releases and facilitate core cooling in the event of a loss-of-coolant accident (LOCA). The cooling process requires water from the break and from containment spray to be collected in a sump and recirculated through the emergency core cooling (ECC) and containment spray (CS) systems. The containment sump design incorporates a screen that protects systems, structures, and components in the CS and ECC system flow paths from the effects of debris that could be washed into the sump. There has been concern that fibrous insulation could form a mat on the screen that would obstruct flow.

Concerns have been raised about the potential for corrosion products to significantly block flow across a fiber bed and therefore increase the head loss across the bed. Among the materials that are found inside containment and are susceptible to chemical reactions with the post-LOCA solution are aluminum, zinc, carbon steel, copper and non-metallic materials such as paints, thermal insulation (e.g., cal-sil, fiberglass), and concrete.

Industry, with support from the NRC and EPRI, has developed a test plan to study possible interaction between the corrosion products (e.g., gelatinous material, agglomerates, etc.) and the effects of those products on filtration. The test plan addresses two objectives:

Guidance to address the effects of corrosion products on head loss is deferred until the testing is completed and the data have been appropriately evaluated.

8 SUMMARY

The purpose of this document is to provide licensees with a guidance for evaluating the post-accident performance of the containment sump screen for a pressurized water reactor (PWR). The approach taken in developing this guisance was to define a common and consistent approach that was applicable to all PWRs. This common and consistent method is termed the *"Baseline Evaluation Method."* Above and beyond the Baseline Evaluation Method, refinements to the analytical methods and design considerations are defined. Also, additional design considerations that should be accounted for in evaluating current or future designs are identified. Finally, a risk-informed approach to break size selection is also provided.

PWRs vary greatly in containment size, floor layout, sump configuration, required ECCS flows, insulation types and location, and post-LOCA operational requirements. Since it was evident that one guideline could not encompass all PWRs, this methodology document provides basic guidance on approach and various methods available, but recognizes that the best strategy for each plant could involve a combination of methods and refinements. Each PWR operator, having unique knowledge of specific plant design and operation, is best qualified to determine the optimum solution strategy. As such, this document does not prescribe a specific combination of methods to the user.

The Baseline Evaluation Method, and the guidance to perform the Baseline Evaluation Method, provides a conservative approach for evaluating the generation and transport of debris to the sump screen, and the resulting head loss across the sump screen. If a plant uses this method and guidance to determine that sufficient head loss margin exists for proper long-term Emergency Core Cooling (ECC) and Containment Spray (CS) function, no additional evaluation for head loss is required.

Given is Section 1 is an introduction to the PWR strainer debris issue, including a historical review describing the steps that led to the current understanding. Section 2 is a high-level summary of the overall process considerations that need to be addressed during the evaluation process, while Section 3 describes a Baseline Evaluation Method that may be applied to all PWR's and provides sample calculation using the Baseline Evaluation Method. In Section 5, refinements in administrative control and design are discussed. Section 6 provides a guidance on a risk-informed evaluation. Section 7 provides guidance for additional design considerations.

The current document has several open areas that require either more study or testing to address. They include the treatment of long-term chemical effects and calcium silicate head loss correlations. This document also does not address the implementation and/or licensing of any design or operational changes resulting from the use of the evaluation methodology.

9 REFERENCES

1. Regulatory Guide 1.82, Revision 3, "Water Sources for Long-Term Recirculation Cooling Following a Loss-Of-Coolant Accident," U.S. Nuclear Regulatory Commission, November 2003.

2. NEI 02-01, Revision 1, "Condition Assessment Guidelines: Debris Generation Sources Inside PWR Containments," September 2002.

3. ANSI/ANS 58.2-1988, "American National Standard Design Basis for Protection of Light Water Nuclear Power Plants Against the Effects of Postulated Pipe Rupture," 1988.

4. NEDO-32686, "Utility Resolution Guidance for ECCS Suction Strainer Blockage," Revision 0, Boiling Water Reactor Owner's Group, November 1996.

5. White Paper, "Defining Coating Destruction Pressures and Coating Debris Sizes for DBA-Qualified and Acceptable Coatings in Pressurized Water Reactor (PWR) Containments," J. R. Cavallo, April 19, 2004, included as Appendix A.

6. NUREG/CR-6808, "Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance," U.S. Nuclear Regulatory Commission, February 2003.

7. N-REP-34320-10000-R00, "Jet Impact Tests – Preliminary Results and Their Applications," Ontario Power Generation, April 2001.

8. Thermal Insulation Handbook, by William C. Turner and John F. Malloy, Robert E. Krieger Publishing Company, Inc., 1981.

9. Product literature provided by JPS Glass Fabrics on Insulbatte® and Tempmat@ insulation products (www.jpsglass.com).

10. Product literature provided by Thermal Ceramics, Inc. on Kaowool Blanket Products (www.thermalceramics.com).

11. Certificate of Analysis from Tech-Flo, supplier of Perlite Filteraids, provided by IIG, Inc.

12. Product literature provided by Thermal Ceramics, Inc. on Min-K Insulation (www.thermalceramics.com).

13. Product literature provided by Microtherm, Ltd. (http://www.microtherm.uk.com).

14. Military Specification MIL-I-16411F, Section 3.3.

15. Microporous Theory, Technical Notes on MinK, Document Number TN01301, provided by Thermal Ceramics, Inc.

16. Rao, D. V., et al, NUREG/CR-6369, Vol 1: Drywall Debris Transport Study-Final Report; Vol 2: Drywell Debris Transport Study: Experimental Work-Final Report, February 1998.

17. Zigler, G., et al, NUREG/CR-6224; Parametric Study of the Potential for BWR ECCS Strainer Blockage due to LOCA Generated Debris, September 1995.

18. Aldinger, T. I., R. A. White, and R. A. Manley, Performance of Containment Coatings During a Loss of Coolant Accident, Bechtel Power Corporation, November 10, 1994 (In Volume III of the Utility Resolution Guidance (URG) for ECCS Suction Strainer Blockage, BWROG, November 1996).

19. “ASHRAE Handbook of Fundamentals,” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1972.

20. Strok & Koral, “Handbook of Air-Conditioning, Heating, and Ventilation,” Second Edition, Industrial Press, 1965.

21. Bostelman, Jan and Gilbert Zigler, “Failed Coatings Debris Characterization,” BWRG Containment Coatings Committee, July 10, 1998.

22. Shaffer, C. J., et al., "BLOCKAGE 2.5 Reference Manual,” NUREG/CR-6371, December 1996.

23. Leonard, M. T., Arup Maji, et. al., “Debris Accumulation & CalSil Head Loss Testing—Findings & Preliminary Conclusions,” Presentation at GSI-191 Public Meeting, Albuquerque, NM, March 5, 2003.

24. NEA/CSNI/R (95) 11, “Knowledge Base for Emergency Core Cooling System Recirculation Reliability,” Prepared by U.S. Nuclear Regulatory Commission for the Principal Working Group 1 (PWG-1), International Task Group, Committee on the Safety of Nuclear Installations, Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA), February 1996.

25. NUREG/CR-6762, “GSI-191 Technical Assessment,” U.S. Nuclear Regulatory Commission (2002).

26. SER on Topical Report OCF-1, “Nuclear Containment Insulation System,” U.S. Nuclear Regulatory Commission, December 8, 1978.

27. “Air Blast Destructive Testing of NUKON® Insulation Simulation of a Pipe Break LOCA,” Performance Contracting Inc., dated October 1993.

28. EPRI Report 1003102, Revision 1, “Guideline on Nuclear Safety-Related Coatings,” (formerly EPRI TR-109937).

29. N-REP-34320-10000-R00, “Jet Impact Tests – Preliminary Results and Their Applications,” Ontario Power Generation, April 2001.

30. Product literature provided by Belform Insulation, Ltd. (http://www.belform.com).

31. Performance Contracting Inc. Specification Sheet: 3M InteramTM E-50 Series.

32. Product literature provided by Armil C.F.S. (http://www.armilcfs.com).

33. USG Material Safety Data Sheet; MSDS No. 01030, Rev 3, dated October 1, 1999.

34. Product literature provided by Performance Contracting Inc (http://www. promatec.com).

35. “Flow of Fluids Through Valves Fittings and Pipe,” Crane Technical Paper No. 410, 1981.

36. “The Hydraulics of Open Channel Flow, An Introduction,” Chanson Hubert, Arnold Publishing, 1999.

37. “Volunteer Plant Containment Pool Flow Analysis,” David DeCroix, Los Alamos National Laboratory, Nuclear Design and Risk Analysis Group, presented at NRC Public Meeting, March 5, 2003.

38. “Containment Sump Channel Flow Modeling,” presented at NEA/NRC Workshop on Debris Impact on Emergency Coolant Recirculation,” Westinghouse Electric Co., February 2004.

39. Idelchek, I. E., Handbook of Hydraulic Resistance, Hemisphere Publishing Co., Academy of Sciences of the USSR, 1986.

40. Miller, Donald S., “Internal Flow, A Guide to Losses in Pipe and Duct Systems,” The British Hydromechanics Research Association, 1971.

41. GE Nuclear Energy, “Utility Resolution Guide for ECCS Suction Strainer Blockage,” Prepared by BWR Owners’ Group, NEDO-32686-A, October 1998.

42. Continuum Dynamics, Inc., “Evaluation of Paint Chip Head Loss on Vertically Oriented Zion Station Screen: July 1997 Test Phase,” July 1997.

43. Continuum Dynamics, Inc., “Debris Transport and Head Loss Test Report For the Millstone Unit II Sump,” February 1999.

44. Duke Engineering & Services, “ECCS Strainer Performance Analysis for Min-K,” TR-VT5900.01, October 1997.

45. New York Power Authority and ITS Corporation, "Characterization of Head Losses Due to Mixed Fibrous and Micorporous Insulation Debris," October 1999.

46. Alden Research Laboratory, Inc., "Head Loss of Fibrous Thermal Wrap Insulation Debris and Sludge for BWR Suction Strainers," 265-95/M787F, December 1995.

47. Fortum Engineering Ltd., "Comparison of Resulting Differential Pressure Over Sump Screen Using Different Types of Fibrous Debris Generated With High Pressure Water/Steam Impingement," May 1999.

48. Science and Engineering Associates, Inc. "Experimental Investigation of Head Loss and Sedimentation Characteristics of Reflective Metallic Insulation Debris," SEA No. 95-970-01-A:2, May 1996.

49. Duke Engineering & Services, "Test Evaluation Report for Test TPP-VL0400-005: LaSalle Strainer Fiber and RMI Debris Tests," TPP-VL04000-006, June 1998.

50. Finnish Centre for Radiation and Nuclear Safety (STUK), "On the Mechanics of Metallic Insulation Pressure Drop Generation," Juhani Hyv@rinen and Nina Lahtinen, May 1999.

51. Finnish Centre for Radiation and Nuclear Safety (STUK), "Metallic Insulation Behaviour in a LOCA," Dr. Juhani Hyv@rinen, October 1999.

52. Swedish Nuclear Power Inspectorate, "The Effect of Chemicals on Strainer Filtration, Final Report: Laboratory Tests at Various pH Levels," SKI Report 95:4, January 1995.

53. Ontario Power Generation, "Status on Issue of LOCA-Generated Debris," C. Slongo, October 1999.

54. NUREG/CR-6773 (LA-UR-02-6786), "GSI-191: Integrated Debris-Transport Tests in Water Using Simulated Containment Floor Geometries," Los Alamos National Laboratory, December 2002.

55. NUREG/CR-6772 (LA-UR-02-6882), "GSI-191 Separate Effects Characteristics of Debris Transport in Water," August 2002.

56. C.D.I. Report 96-06, "Air Jet Impact Testing of Fibrous and Reflective Metallic Insulation," Revision A-Final Draft, September 1996.

57. NUREG/CR-2792, "An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions," U.S. Nuclear Regulatory Commission, Washington, D.C., September 1982.

58. LA-UR-0104083, Revision 1, "GSI-191 Technical Assessment: Parametric Evaluations for Pressurized Water Reactor Recirculation Sump Performance," D. V. Rao, B. Letellier, C. Schaffer, S. Ashbaugh, and L. Bartlein, August 2001.